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A JOURNAL ON ACCELERATORS, INSTRUMENTATION
AND TECHNIQUES IN NUCLEAR PHYSICS

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CONTENTS

F. W. K. FIRE, G. W. REID and J. F. GALLAGHER, High resolution neutron time-of-flight experiments using the Harwell 15 MeV linear electron accelerator	309
R. N. GLOVER, Aluminium proportional counter for the measurement of low fast neutron flux	316
R. N. GLOVER, Photofission in fission chambers	320
J. J. BURGERJON, S. J. DU TOIT and C. A. J. KRITZINGER, The Pretoria cyclotron	323
KRISTIAN SKARSVÅG, Multiple fast coincidence unit	336
K. S. SUBUDHI, Function of the collecting electrode in a Van de Graaff generator	341
A. M. HILLAS and R. M. TENNENT, High speed counter chronometer	344
L. COSTRELL and R. E. BRUECKMANN, Charge-storage pulse-height analyzers for use with pulsed accelerators	350
MOSTAFA F. AMR EL-SAYED, A nuclear method for determining very low vapor pressures (Letter to the Editor)	359
Author Index	361
Subject Index	363



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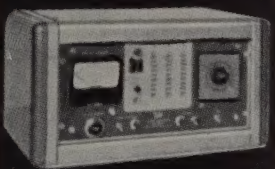
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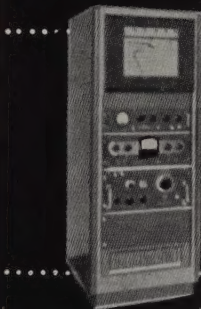


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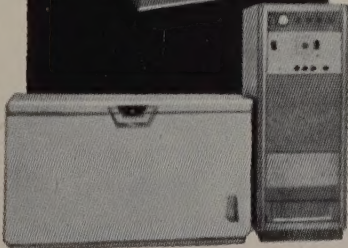
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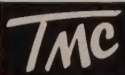
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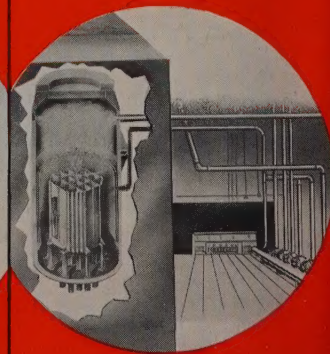
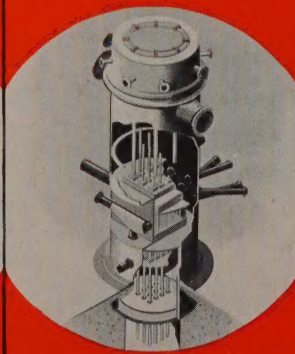
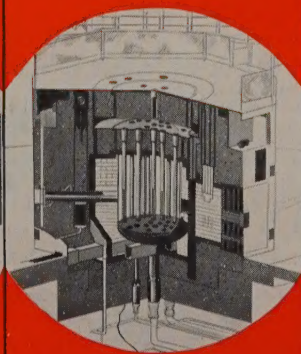
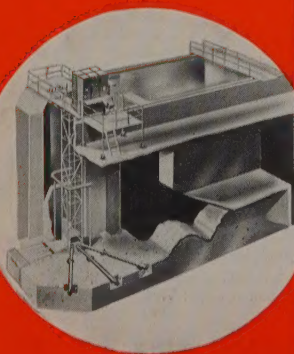
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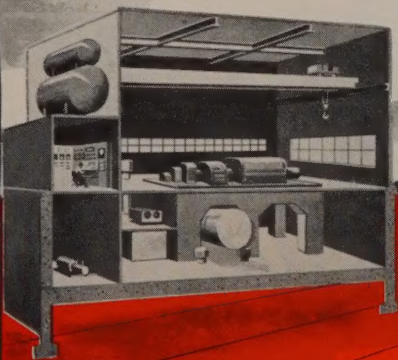
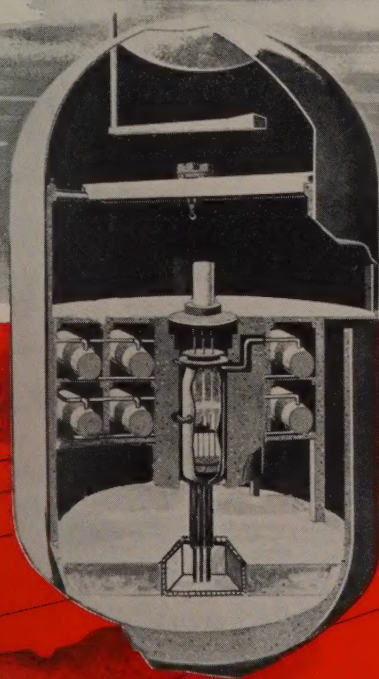
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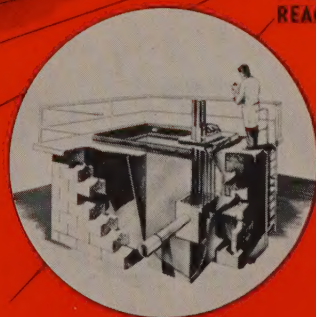
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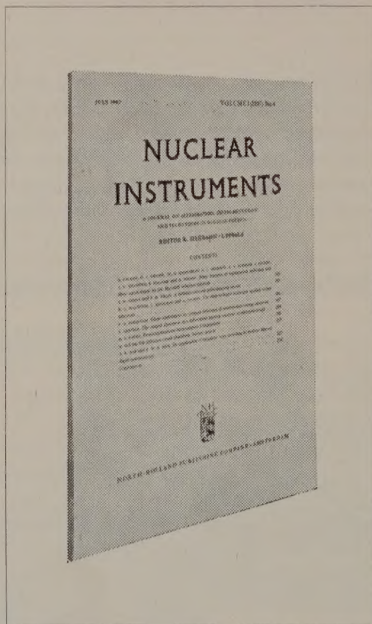
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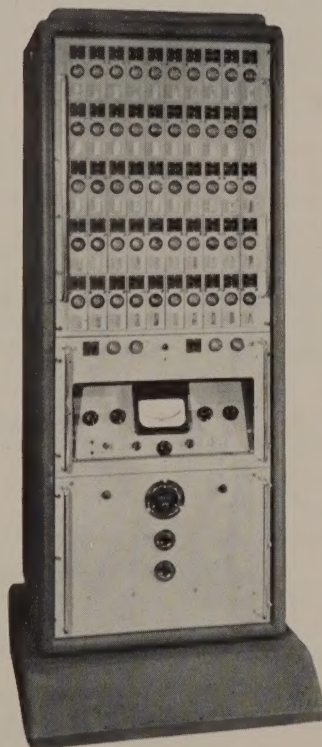
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HIGH RESOLUTION NEUTRON TIME-OF-FLIGHT EXPERIMENTS USING THE HARWELL 15 MeV LINEAR ELECTRON ACCELERATOR

F. W. K. FIRK, G. W. REID and J. F. GALLAGHER†

Atomic Energy Research Establishment, Harwell, Didcot, Berks.

Received 1 November 1958

A technique is described for producing neutron pulses of 0.25 μsec duration at 400 p.p.s. The electron gun of the Harwell 15 MeV linear accelerator is pulsed from an external modulator during the period of the normal radio frequency pulse of 2 μsec duration. Using timing channels of 0.2 μsec duration and a flight path of 31.8 m a nominal resolution

of 8 $\mu\text{sec m}^{-1}$ is obtained. The neutron output during the 0.25 μsec pulse is approximately 60% of the output obtained when using the normal 2 μsec electron pulse. Total cross section measurements using a bismuth sample demonstrate the improved resolution in the energy region of 10 to 20 keV.

1. Introduction

There is an obvious need for improved energy resolution of neutron spectrometers in the energy range of a few electron volts to tens of kilovolts. Using a pulsed neutron source and time-of-flight equipment this improved resolution is best achieved by reducing the duration of the neutron burst and, at the same time, reducing the duration of the timing channels. Such improvements in the performance of the Harwell 15 MeV linear accelerator and associated neutron time-of-flight equipment are described.

Details of the 15 MeV machine and associated neutron spectrometer have been given previously^{1,3}). A brief description of the equipment will, however, be useful in this paper. A magnetron operating at 3000 Mc/s is pulsed from a crystal controlled oscillator at a repetition rate of 400 p.p.s. The duration of each R.F. pulse is 2 μsec and the peak power developed during the pulse is 1.8 MW. The pulse that triggers the magnetron is also used to obtain an electron burst from a tungsten filament at the input to the corrugated waveguide of the accelerator. This negative pulse is 50 kV in amplitude.

The accelerated electrons produce a pulse of photo-neutrons in a block of natural uranium.

The duration of this photo-neutron pulse is $< 1 \mu\text{sec}$ ²): the reduction (from 2 μsec) in the duration of this pulse is due to the time required to establish peak power in the waveguide system.

Normally, timing channels of 1 μsec duration are used and with the longest flight path available (56.7 m) give a resolution of 18 $\mu\text{sec/m}$.

In order to produce an electron burst of short duration ($\approx 0.2 \mu\text{sec}$) with a minimum amount of modification, an external electron gun modulator was designed to replace the existing 2 μsec pulse used in normal operation.

The external modulator is required to produce a negative voltage pulse of duration $\approx 0.2 \mu\text{sec}$ and amplitude $> 50 \text{ kV}$. The duration of the R.F. pulse from the magnetron is left unaltered. By triggering the external modulator from a phasing unit it is possible to pulse the electron gun at any time during the normal R.F. pulse to the accelerator. The phasing unit is required to produce a continuously variable pulse with respect to the crystal controlled oscillator pulse used to trigger the standard magnetron modu-

¹) C. F. Bareford and M. G. Kelliher, *Philips Tech. Rev.* **15** (1953) 1.

²) J. E. Lynn, F. W. K. Firk and M. C. Moxon, *Nuclear Physics* **5** (1958) 603.

³) P. E. Trier, J. C. Hammerton and E. Wolfendale, *Philips Tech. Rev.* **15** (1954) 325.

† Now at the Royal Radar Establishment, Malvern, Worcs.

lator. A continuous variation in time of $2 \mu\text{sec}$ is necessary from the phasing unit. This output pulse should be free from time jitter.

A convenient method of obtaining timing channels of short duration is to produce voltage pulses whose amplitudes are proportional to the neutron flight times. These pulses are then pulse height analysed. Such a method is extremely flexible: timing channels of duration varying from tens of μsecs to several $\text{m}\mu\text{sec}$ are readily obtainable. A suitable time-to-amplitude converter is described (subsection 2.3).

2. Design of the system

2.1. THE PHASING UNIT

This unit triggers the hydrogen thyatron in the external electron gun modulator. The requirements are that the pulse to the grid of the thyatron should be $\approx 300 \text{ V}$ amplitude, not less than $2 \mu\text{sec}$ duration and the rate of rise of the front edge should be greater than $1000 \text{ V}/\mu\text{sec}$. In addition, an accurate variation in time relative to an incoming trigger pulse is required in order to phase the $0.2 \mu\text{sec}$ electron gun pulse with reference to the $2 \mu\text{sec}$ R.F. pulse in the accelerator.

A 1:4 step-up pulse transformer is connected directly to the grid of the thyatron thus reducing the required amplitude of the pulse from the phasing unit to 75 V .

The continuously variable time delay is derived from a ringing coil circuit in the cathode of a valve. A similar technique has been used previously with the 15 MeV accelerator³) and has proved extremely reliable and free from jitter.

The circuit diagram is given in fig. 1.

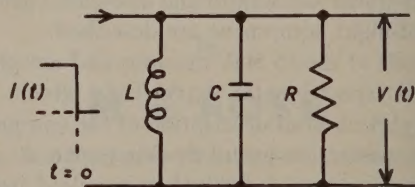
The blocking oscillator V_1 is triggered by a negative pulse occurring $5 \mu\text{sec}$ before the R.F. pulse in the accelerator. A diode "pump" circuit ($\frac{1}{2} V_2$) is used to lengthen the negative pulse obtained from the anode of V_1 . This negative pulse of 150 V amplitude suddenly cuts off the standing current of 16 mA flowing through the valve V_3 and the inductance L (10 mH). Consequently, the LC circuit in the cathode of V_3 oscillates commencing with a

negative going sinusoid. The period of this sinusoid is determined by the value of the variable capacitor C since the inductance is fixed. The positive going portion of the sinusoid is heavily damped by the low impedance of the grid-cathode path of V_4 and no further oscillation occurs. A positive square voltage pulse is produced in the anode of V_4 the duration of which is equal to the half period of the sinusoid. The square voltage pulse obtained from the anode of V_5 has a duration (determined by a short circuited delay line) of $3 \mu\text{sec}$. A cathode follower output stage, V_6 and V_7 , provides an output pulse of 75 V into an impedance of 100Ω .

Design considerations of the LC circuit

A negative pulse applied to the control grid of V_3 cuts off the current normally flowing through the inductance L . The transient behaviour of the LCR circuit in the cathode of V_3 is readily determined by using the Laplace transform method. (R is the damping resistance across the LC circuit).

Let $I(t)$ be the current normally flowing through V_3 . The valve may be regarded as a generator of a current step function of amplitude $-I(t)$. For



the transient voltage $V(t)$ developed across the LCR circuit we have on taking the Laplace transforms of the voltage and current:

$\bar{V}(p) = \bar{I}(p) \cdot \bar{Z}(p)$ since the initial conditions are zero. $\bar{Z}(p)$ is the generalised impedance of the network and is given by:

$$\bar{Z}(p) = \frac{p}{C[(p + \alpha)^2 + \omega^2]}$$

where $\alpha = 1/2 CR$ and $\omega^2 = 1/LC - 1/(2 CR)^2$

$$\bar{V}(p) = \frac{-I\omega}{\omega C[(p + \alpha)^2 + \omega^2]} \text{ since } \bar{I}(p) = -I/p.$$

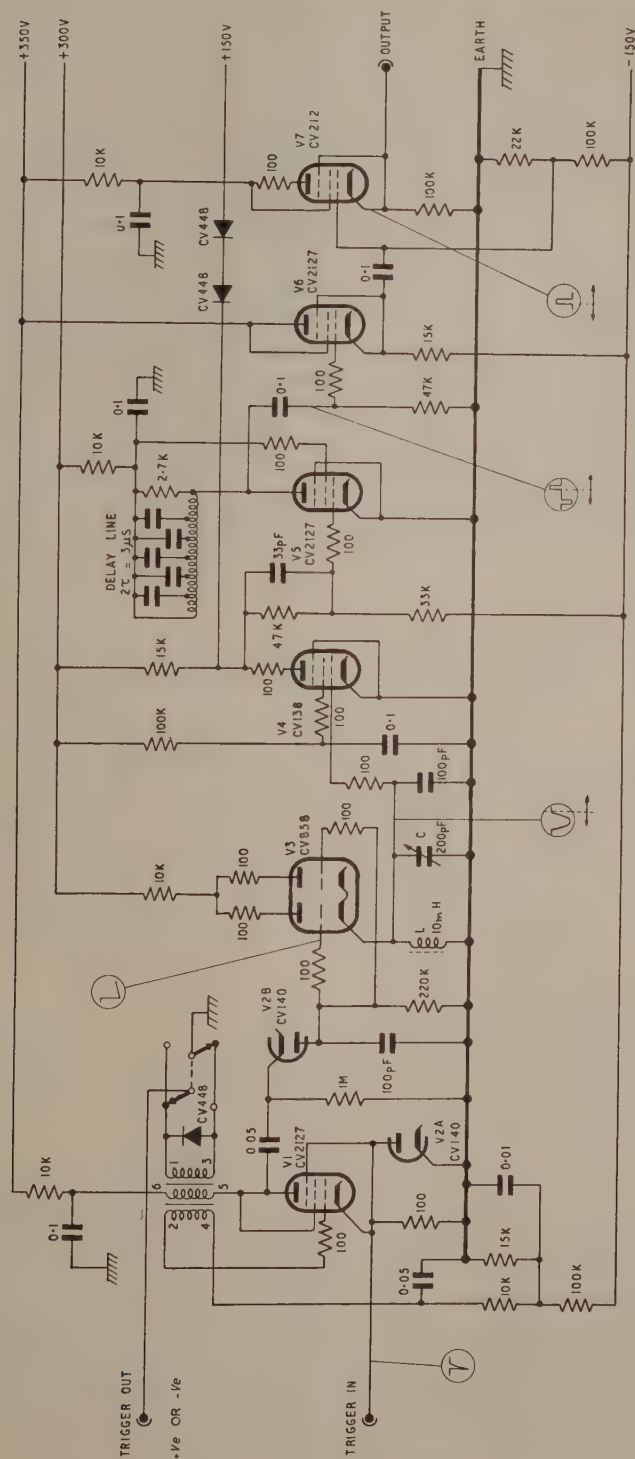


Fig. 1. The circuit diagram of the phasing unit.

Magnetizing current, i_m , will however soon build up in the magnetizing inductance L_m of the transformer. This current increases even further due to saturation of the core. As the voltage across C falls to zero C_g will discharge into the transformer, the value of the current being controlled by the value which i_m has reached. Normally, C_g cannot discharge through C and the thyatron as this is a uni-directional switch. The pulse tail will thus depend largely on the final magnetizing inductance of the pulse transformer and hence on the B - H characteristic of the core material.

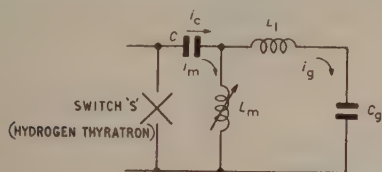


Fig. 2(b). Simplified diagram of the discharge circuit.

The Pulse Transformer

This is designed to use two existing 0.002" Hypersil "C-cores" which were known to be of only average quality. Only a few turns were used and the winding length kept long to give a low value of L_1 and a suitable value of L_m .

Transformer details are as follows:

Turns Primary 3 Secondary 23, 6 S.W.G.

Perspex former of rectangular cross section

Pri. $2\frac{1}{8}" \times 4\frac{3}{4}" \times 7"$

Sec. $3" \times 5\frac{5}{8}" \times 7"$

Window $4\frac{3}{8}" \times 7\frac{5}{8}"$.

Core area $1\frac{1}{4}" \times 4" = 5$ sq. in.

The transformer is oil immersed in a water cooled tank. 0.5 μ F equalising capacitors are placed across the bi-filar.

At a frequency of 1000 c.p.s. the following characteristics were obtained:

Pri. magnetizing inductance = 32.5 μ H.

Sec. magnetizing inductance = 1.75 mH

Pri. leakage inductance $\simeq 3$ μ H

Sec. leakage inductance = 75 μ H

Total gun capacitance $\simeq 100$ pF.

The modulator has given reliable operation for several months. The pulse shape is shown in fig. 2(c) and is found to be satisfactory. It should, however, be possible to obtain a better pulse shape if a rectangular loop core material

such as permalloy "F" were used for the pulse transformer. This should also enable a variable pulse width to be obtained by biasing the core. Probably the most satisfactory solution to this problem would be a triode gun with which even shorter and sharper pulses could be obtained.

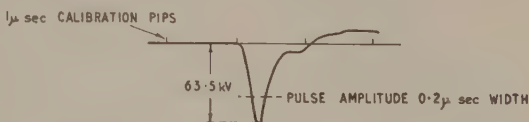


Fig. 2(c) Oscillogram of the electron gun voltage pulse.

2.3. THE TIME-TO-AMPLITUDE CONVERTER

This unit is designed for use with a 100 channel pulse height analyser (A.E.R.E. type 1524) giving 100 timing channels each of approximately 0.2 μ sec duration. A further requirement is to lengthen the output pulse to 100 μ sec so that the pulse can be displayed across the screen of an oscilloscope and photographed through a wedge analyser.

The circuit diagram is shown in fig. (3a) and the waveforms in fig. (3b). The circuit is essentially a "bootstrap" time base whose linear rise commences when a square negative voltage pulse cuts off the standing current through the pentode V_5 . The capacitor C continues to charge up linearly until the termination of the negative pulse applied to the control grid. If, however, a signal pulse arrives during the time interval T_1 the charging current is switched off by the application of a negative voltage pulse to the diode D_1 . This same negative pulse ensures that the pentode V_5 (which has a "short suppressor grid-base") remains cut off after the termination of the control grid pulse. During the period T_2 the capacitor C is isolated and the voltage across it is almost constant (the voltage droop is < 1 mV/ μ sec). The precision with which the linear ramp stops is determined by the rate of fall of the leading edge of the negative pulse in the anode V_4 . This is approximately 1 m μ sec/volt and is governed by the shape of the pulse at the anode of the blocking oscillator V_3 .

Only those signals which arrive during the interval T_1 trigger the blocking oscillator via the gating valve V_2 . In the absence of a signal pulse

R.F. power thus resulting in a maximum output of photo-neutrons from the uranium target. This point is shown by the fact that the neutron output from the machine when using the 0.2 μ sec gun modulator is $\approx 60\%$ of the normal neutron output obtained using a 2 μ sec electron gun pulse triggered at the same time as the magnetron. A further contribution to the improved neutron output relative to normal operation is attributed to the increased energy of the electrons due to the lighter beam current loading of the accelerator when using the narrow pulse. The neutron yield in uranium rises rapidly in the region of 15 MeV electron

energy⁵). An increase of approximately 1 MeV in maximum electron energy is estimated for the 0.2 μ sec pulse conditions; this corresponds to an increase in neutron yield of approximately 15%.

Acknowledgements

The authors wish to acknowledge the late Mr. G. T. Hawkins whose contribution to the design and construction of the modulator was considerable. They also wish to thank Mr. M. C. Moxon who assisted in the computation of the total cross section data.

⁵) A. W. Aikin, Proc. Phys. Soc. A 69 (1956) 419.

ALUMINIUM PROPORTIONAL COUNTER FOR THE MEASUREMENT OF LOW FAST NEUTRON FLUX

R. N. GLOVER†

*Vickers-Armstrongs (Eng.) Ltd., Barrow-in-Furness,
(attached to Naval Section, A.E.R.E., Harwell)*

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A simple aluminium-walled proportional counter has been developed to measure low fast neutron flux by irradiation of the counter itself and subsequent counting of the β -rays from the 9.8 min Mg^{27} activity produced by the (n,p)

reaction. The operational characteristics are described and the sensitivity discussed. The counter is capable of detecting a fast neutron flux $\approx 10^3 \text{ n}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$.

1. Introduction

The measurement of very low fast neutron flux ($< 10^5 \text{ n}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$) by means of threshold detectors is not possible by conventional methods, i.e. irradiation of small quantities of materials and subsequent counting by standard techniques, because of the small amount of activity induced. Fission chambers cannot be used in water in regions of low fast flux since photofission of their fissionable content becomes the predominant effect¹). For fast neutron detection the (n,p) reactions in sulphur, phosphorus and aluminium may be used. Sulphur irradiations are commonly carried out to measure low fluxes but suffer from two disadvantages (1) the need for long irradiation periods because of the 14 day half-life of P^{32} , (2) the need to separate chemically the P^{32} from the sulphur and maintain a constant separation efficiency. Hence using aluminium a technique which is simple, sensitive and needs only short irradiations was developed. The Mg^{27} produced has a 9.8 min half-life so that a 40 min irradiation gives 94% of saturation activity. The method was to use the aluminium as the cylindrical wall of a small counter, the counter itself being irradiated.

† Present address: Dept. of Nuclear Physics, Australian National University, Canberra, A.C.T.

2. Design of the Counter

The detailed design is shown in fig. 1. The aluminium cylinder was 3" long $\times$ 1" diam. These dimensions were chosen since the flux

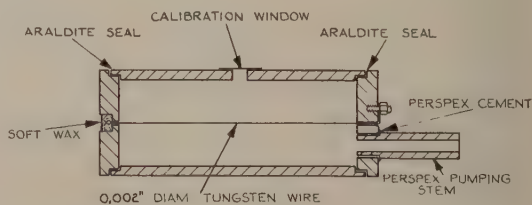


Fig. 1. Section through aluminium walled counter.

distribution in any plane parallel to the reactor core face was known to be very flat so that, with the counter axis lying in such a plane, there was negligible flux variation along its length. The wall thickness was $\frac{1}{8}$ ". This is greater than the maximum energy of the β -rays (1.8 MeV) and hence could be somewhat reduced without affecting the sensitivity of the counter. The end-pieces were made of perspex since this material does not become radioactive on irradiation. A vacuum tight, though not particularly robust, seal was obtained between perspex and aluminium by the following

¹) R. N. Glover, Nuclear Instruments 3 (1958) 320.

procedure. The perspex end was machined so that it was slightly too large to fit the aluminium cylinder and annealed. The cylinder was then heated till the ends (which were not heated) just fitted and, after it had cooled, cold setting. Araldite D was used as a sealing compound. The tungsten wire, diameter 0.002", was tied at one end to a loop of thick wire, drawn taut at the other, wound round an 8BA rod and held by washers and a nut. The 0.020" holes through which the wire passed at each end were sealed with soft wax (1:1 beeswax and resin). The calibration window was 0.004" aluminium foil sealed round the edge with wax. No trouble was experienced with any of these wax seals.

3. Operation of the Counter

The counter was operated as a proportional counter rather than a Geiger for several reasons viz.

1. The "plateau" is long and flat. It is obtained by increasing the gain until all the β -rays from the walls are being detected. No further increase in count rate should then be observed with increasing gain until noise level is reached. Between these two points the counter is essentially independent of gain fluctuations as is shown below.

2. Proportional counters are less variable. Unlike Geigers, similar counters normally operate at the same voltage and give the same count rate if exposed to the same activity.

3. The operation of a proportional counter can be rapidly checked by observing the pulse height and resolution of an X-ray line.

4. The nuisance of applying dead-time corrections is avoided.

Helium, methane, neon and nitrogen if irradiated give only activities which are of very short half-life (< 40 sec) or very long (> 5000 y). Hence to enable measurement of the 9.8 min Mg^{27} β -activity to start as soon as possible after an irradiation the counters were filled to a pressure of 1 atm with a mixture of 10% methane and 90% crude neon. On irradiating the counter in a cadmium container to avoid activities due to 2.3 min Al^{28} and also to im-

purities in the aluminium, only two half-lives were observed corresponding to Mg^{27} and Na^{24} , the latter expected from the (n,α) reaction in aluminium and of intensity $\approx 1\%$ of the Mg^{27} activity. However it proved difficult to calibrate with the 9.3 keV Ga K X-rays from Ge^{71} perhaps due to impurities in the crude neon. It was felt desirable, at least until more was known about the behaviour of the counters, to use also the customary 10% methane, 90% argon mixture. In addition, larger pulses would be obtained from the counter since, because of the greater density of argon, more ionisation would be produced by a β -ray before it hit the wall. The X-ray peak was easily observed with this gas mixture. Several samples of argon gas irradiated in sealed glass bottles inside cadmium containers all showed a small amount of 110 min activity. This is due to A^{41} produced by neutrons not absorbed in, or else thermalised by, the cadmium container. To avoid this activity the counter was evacuated before irradiation and afterwards connected to a glass bottle containing argon-methane mixture at such a pressure that, on opening, it filled the counter to 1 atm. Since only the tubing connecting bottle and counter had to be evacuated, the process of filling the counter could be performed quickly.

Although the counter contains no guard or field tubes, no spurious pulses were observed at several hundred volts above the normal operating voltages of approximately 1900 V for the argon-methane and 1750 V for the neon-methane. The counter was surrounded by a ring of Geiger counters operating in anticoincidence with it, and shielded by a 4" lead castle. The counter pulses were amplified by a type 1430 (head amplifier adjusted to gain $\times 8$) and fed to a scaler biased at 5 V. If the count rate was low the counter background could be reduced by using the anticoincidence ring, the Geiger pulses being fed to a square wave generator and then operating a simple anticoincidence gate. The background of the counter under lead was 23 cpm, and with the anticoincidence ring in addition 7.6 cpm. Fig. 2 shows, for a counter

filled with the argon-methane mixture, the typical variation of count rate with amplifier gain. The measurements were made with a counter irradiated for a sufficient length of time

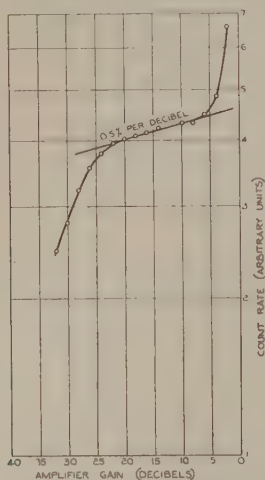


Fig. 2. Variation of count rate with amplifier gain.

to build up appreciable Na^{24} activity (10^5 cpm) in the walls. It can be seen that there is a very good plateau extending over 14dB change in amplifier gain and with a slope of approximately 0.5% per dB. A similar plateau was obtained when the counter was filled with neon-methane, and the actual count rate observed, allowing for the decay of the Na^{24} in the interim, was the same as for argon-methane. The counter was equally insensitive to fluctuations (± 100 V) in the E.H.T. voltage. Since it could be deduced from the height of the Ga X-ray line in the argon-methane mixture that at 18 dB gain the 5 V discriminator bias on the scaler corresponded to the detection of pulses of energy > 250 eV, it is not surprising that all the β -rays are being recorded although the small dimensions of the counter and high energy of the β -rays mean that only a very small fraction of the β -ray energy is spent in the counter. No significant change in the plateau was ever observed on pumping out and refilling a counter. Using the Ga X-ray line no significant gain change was observed in an argon-methane filled counter

over a period of several days. Therefore careful outgassing of the perspex seems unnecessary. The count rate of several counters was observed to be the same after similar irradiations as is to be expected if the dimensions are identical.

In short, a good plateau and high stability, and hence good reproducibility of results, appear to be characteristic of these counters. The count rate is independent of the counter used and of whether the filling is argon-methane or neon-methane.

4. Flux Measurement and Sensitivity

A layer of 0.001" aluminium foil was wrapped tightly round the counter and counter and foil irradiated in a cadmium container. The foil was then trisected, folded and counted as three 0.002" thick sources in three flow counters, the decay of both the 9.8 min and 14.9 h activities being followed. The decay of these activities in the aluminium counter was also noted. Hence the activities at the end of the irradiation were determined graphically. The activity/sq. cm of the wrapping foil agreed with that of an aluminium foil (normal size used was of area 4.75 cm², thickness 0.004" i.e. 27.5 mg/cm²) located at the geometric centre of the counter, when both were corrected for self-absorption and backscattering²⁾. The observed count rate of the counter was determined to be a factor of 53 greater than that which would be observed, i.e. uncorrected, from a normal foil at the geometric centre. This factor appeared to be independent of whether the counter was filled with argon-methane or neon-methane or whether the Mg^{27} or Na^{24} activity was measured. Hence for this counter size the 9.8 min activity at the end of the irradiation is divided by 53 to obtain the count rate of a normal foil at the geometric centre and the flux then calculated in the usual manner²⁾ after correcting the normal foil count rate, in this case hypothetical, for self-absorption and backscattering.

The counter will detect a small percentage of the Mg^{27} 0.84 MeV γ -rays. Since the number of γ -rays is proportional to the β -activity their

²⁾ R. N. Glover, A.E.R.E. R/R 2688 (1958).

detection merely slightly increases, and is automatically included in, the comparison factor between counter and foil. However if the Geiger ring is used it may detect $\approx 5\%$ of the γ -rays. It can be shown that only $\approx 10\%$ of the β -rays produced in the aluminium wall penetrate to the counting volume. Therefore the correction for counts lost due to a γ -ray coincident with a detected β -ray being itself detected by a Geiger counter and so closing the anticoincidence gate is negligible.

The sensitivity of the counter relative to the foils used is, of course, influenced by the backgrounds of the counters. These are 33 cpm in a 2" lead castle for the flow counters and 7.6 cpm for the aluminium counter as mentioned earlier. These represent a further increase in relative sensitivity by a factor ≈ 4 . Hence the counter is capable of detecting a fast neutron flux $\approx 10^3 \text{ n}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$. The foil technique can be increased in sensitivity by using a thick aluminium source almost filling the flow counter tray (2" diam). The relative count rate obtained by the two methods then depends on the relative surface area. In the present case the aluminium counter count rate would be a factor ≈ 3

greater than the maximum foil count rate. Consequently the counter would be more sensitive by a factor ≈ 12 than the foil technique at its limit. It should be possible, if necessary, to increase the counter sensitivity further by increasing the area, e.g. if overall size is important, by using two concentric cylinders with several counting wires in the annular region, the inner cylinder being a conventional counter, and also by discriminating against pulses corresponding to energies greater than the maximum energy a β -ray could leave in the counter, thus eliminating for example α -particles from the naturally radioactive impurities in the aluminium.

Acknowledgments

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PHOTOFISSION IN FISSION CHAMBERS

R. N. GLOVER†

*Vickers-Armstrongs (Eng.) Ltd., Barrow-in-Furness
(attached to Naval Section, A.E.R.E., Harwell)*

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During shielding measurements in water on LIDO a large discrepancy was observed between fast neutron flux measurements with fission chambers and those using

activation techniques. This effect is shown to be due to photofission of the fissionable material in the chambers.

1. Introduction

During shielding measurements in LIDO at the "Panel C" facility a large discrepancy was observed between the fast neutron flux in water as measured by fission chambers and by activation techniques. The fast flux line, i.e. variation of fast flux with distance from the front panel of Panel C¹), as determined by aluminium and phosphorus (β -counting of the Mg^{27} and Si^{31} produced by (n,p) reactions) lies parallel to the thermal flux line measured by Cooper²). However the fast flux line as determined by a cadmium covered U^{238} fission chamber, 1000 times depleted in U^{235} , although in agreement with the "aluminium line" to 40 cm from the front panel, diverges rapidly from it beyond that point. At 90 cm the flux as measured by these two methods differs by a factor of 24, the value indicated by the U^{238} fission chamber being approximately six times greater than the measured thermal flux. Similar effects have been observed with thorium, neptunium and plutonium chambers. Thermal flux measurements by Cooper²) using a U^{235} chamber and manganese foils were in excellent agreement up to 120 cm from the front panel but beyond this point rapidly diverged. There is a considerable flux of γ -rays of energy > 5 MeV, particularly 7.7 MeV γ -rays from neutron capture in the core aluminium³). The photofission threshold of U^{238} ,

U^{235} , and Th^{232} are all ≈ 5 MeV⁴). Hence a probable explanation of the observed effect would be photofission of the U^{238} in the chamber. Some experiments to confirm this are described below.

2. Experimental Evidence

Curve "a" (fig. 1) shows the variation in count rate of the U^{238} fission chamber with distance in water from the front panel. The line "b" is obtained from the points in the range 100-130 cm where it is known from the aluminium and phosphorus measurements that the count rate to be expected in the chamber due to fast neutrons is negligible compared to that observed. The corrected fast neutron count rate is given by line "c" obtained by subtracting "b" from "a".

To demonstrate directly that the effect was due to γ -rays, a lead block 6" diam $\times$ 2" thick was suspended immediately in front of the U^{238} fission chamber ($\frac{1}{4}$ " diam, active length 1"). At 40 cm from the front panel, where the count rate was expected to be mainly due to fast neutrons, the lead caused a reduction in count rate by a factor of 1.6. However at 80 cm this factor had increased to 5.0. Using the fast neutron count rate at 80 cm from "c", and an

¹) R. N. Glover, A.E.R.E. R/R 2688.

²) C. Cooper, N.S.S.G. Report No. 12 (1958).

³) J. W. Harrison and J. Butler, unpublished.

⁴) H. W. Koch, J. McElhinney and E. L. Gasteiger, Phys. Rev. 77 (1950) 329.

† Present address: Dept. of Nuclear Physics, Australian National University, Canberra, A.C.T.

attenuation factor of 1.6 for fast neutrons in 2" lead, the attenuation in lead of γ -rays observed by the fission chamber, i.e. those of energy greater than the photofission threshold, was

Th^{232} chambers were almost identical. Knowing the fissionable content and efficiency of each chamber, the ratio of the effective mass of thorium to uranium was shown to be 1.7. The

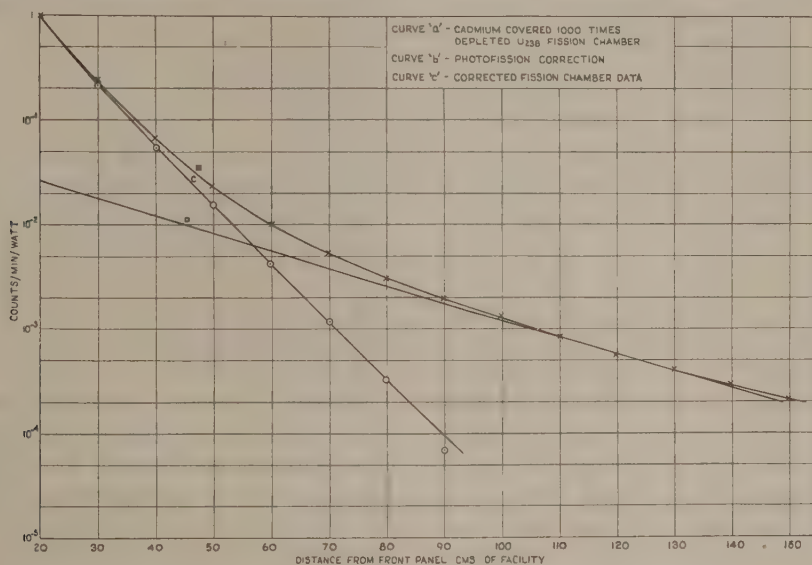


Fig. 1. Count rate of cadmium covered depleted U^{238} fission chamber in water.

deduced to be 7.2. Since 2" lead would be expected to reduce the intensity of γ -rays of 5 and 8 MeV by factors of 11.9 and 15.5 respectively, the measured attenuation, remembering that in a large volume of water there will be considerable scattering round a small absorber, strongly suggests the presence of high energy γ -rays.

Measurements with U^{238} and Th^{232} chambers were also made behind a large (185 cm $\times$ 185 cm) steel plate 7.6 cm thick. If the γ -ray count rate in water at a given distance from the panel (see line "b") is compared with the count rate obtained from a similar line behind the 3" steel plate at 7.6 cm further from the front panel to allow for the steel, then it is found that the steel reduces the intensity by a factor of 5.9. Theoretically 3" steel would be expected to attenuate γ -rays in the energy range 5–10 MeV by a factor of 5.6.

It was observed that beyond 90 cm from the front panel the count rates of the U^{238} and

photofission yield ratio $\text{U}^{238}/\text{Th}^{232}$ has been measured to be 2.0 ± 0.1 for monoenergetic γ -rays of energy 6.3 MeV^{5,6}). Hence if photofission was the predominant effect, the chambers would be expected to give similar count rates.

3. Discussion

The evidence in favour of photofission is very strong. Using line "b" as the photofission contribution to the total count rate, the fast neutron fluxes calculated from "c" are in good agreement with the aluminium and phosphorus results¹).

When the measurements were later extended to 150 cm it was observed that beyond 130 cm the photofission correction line "b" lay below the experimental points. If the correction line had been extrapolated from the points at 140 and 150 cm then the fast flux at 90 cm would

⁵) R. O. Haxby, W. E. Shoupp, W. E. Stephens and W. H. Wells, Phys. Rev. **59** (1941) 57.

⁶) G. C. Baldwin and G. S. Klaiber, Phys. Rev. **71** (1947) 3.

have been about 2.5 times greater than the thermal flux, which is unreasonable. Pair spectrometer measurements by Harrison and Butler³) using a collimated beam have shown that the core γ -ray spectrum consists of a continuous spectrum which hardens appreciably with distance in water and a 7.7 MeV peak due to the aluminium capture γ -ray, which contributes $\approx 75\%$ of the total γ -ray flux above 5 MeV. Unfortunately no measurements are yet available from Panel C. Due to the contribution of scattered γ -rays in a large water tank such as Panel C, the 7.7 MeV γ -rays would not be expected to be so predominant. Qualitatively the continued "flattening off" of the fission chamber count rate beyond 130 cm could be explained by hardening of the γ -ray spectrum and consequently an increase in the mean photofission cross-section since the (γ, f) cross-section is very energy dependent^{7,8,9)}. Hence there is a possibility that the photofission correction should be a gentle curve rather than a straight line. Measurement of the Panel C γ -spectra would enable the variation of photofission contribution with distance in water to be calculated for a given chamber but could not give the magnitude accurately since photofission cross-sections are known only within $\pm 30\%$ ^{7,8)}.

Clearly photofission restricts the applications of fission chambers in water in view of the limited distance from the reactor core within which they may be used and the limited accuracy with which the necessary correction can be applied. For example at 80 cm from the surface of the LIDO core, 50% of the U^{238} fission chamber count rate is due to photofission; at 40 cm there is still a correction $\approx 5\%$. These figures are also

roughly correct for the thorium and neptunium chambers. In regions of low neutron flux increased neutron sensitivity is sometimes achieved by the use of large fission chambers e.g. 2" diam. There is no reason to suppose that the γ -ray sensitivity is not increased by the same factor. Hence the advantage of these chambers will be negated by photofission. The importance of photofission could, of course, be reduced by shielding. At 80 cm from the core surface approximately 4" lead would be required to reduce the photofission correction for the U^{238} chamber to $< 1\%$ of the neutron count rate. However since the response of the chamber depends on the fast neutron spectrum, possible distortion of the spectrum in the lead introduces a further uncertainty. Obviously a lead shield would distort thermal flux measurements.

The distance at which photofission becomes significant in any medium will depend on the relative (n, f) and (γ, f) mean cross-sections for the detector used and relative magnitude of the neutron and gamma fluxes. Since the latter are related to the core structure, e.g. the amount of aluminium present, and the relative attenuation of neutrons and γ -rays in the moderating and/or shielding medium, the possibility of photofission is best checked for any experiment and for any medium by comparing fission chamber and foil measurements e.g. aluminium or manganese. Of the commonly used shielding materials it is to be expected that photofission would be most important in water since it attenuates neutrons relatively well and γ -rays relatively poorly.

Acknowledgments

This work was carried out during attachment to the Naval Section Shielding Group under Mr. C. Cooper. The author wishes to acknowledge the assistance and facilities provided by A.E.R.E., Harwell and the Admiralty.

⁷) L. Katz, T. M. Kavanagh, A. G. W. Cameron, E. C. Bailey and J. W. T. Spinks, *Phys. Rev.* **99** (1955) 98.

⁸) V. A. Korotkova, P. A. Cherenkov and I. V. Chuvalo, *Dokl. Akad. Nauk. S.S.S.R.* **106** (1956) 633.

⁹) R. B. Duffield and J. R. Huizenga, *Phys. Rev.* **89** (1953) 1042.

THE PRETORIA CYCLOTRON

J. J. BURGERJON, S. J. DU TOIT and C. A. J. KRITZINGER†

Nuclear Physics Division, National Physical Research Laboratory, Pretoria

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A brief technical description of the Pretoria fixed frequency cyclotron is given. It is a 112 cm machine which at present accelerates internal deuteron beams of 200 microamperes

to 15 MeV. Interesting features are a double ion source and automatic target removal and despatch mechanism.

1. Introduction

In 1950 South Africa found itself in the position of not having any facilities for nuclear physical research except for some counting equipment used for measuring radioactivity and cosmic radiation. At that time the South African Government decided to establish a national centre for nuclear research within the framework of the National Physical Research Laboratory of the South African Council for Scientific and Industrial Research. The idea was to provide this centre with an accelerator of modest size, and to make the facilities available not only to the physicists of the C.S.I.R., but also to university staff and students.

It is always a difficult task to choose the correct accelerator if it is to be the only one in a country for some length of time. The points which influenced the choice predominantly were the following:

(a) The accelerator had to be such as to enable the performance of as wide a variety of experiments as possible.

(b) It had to keep as large a number of experimental groups as possible occupied, preferably in different fields of nuclear research.

(c) It had to be constructed locally as far as possible to train South African staff in construction techniques and to enable South African industry to gain experience in the manufacture of nuclear equipment.

(d) It had to be modest in price.

† M. S. Livingston, J. Appl. Phys. 15 (1944) 128.

After giving careful consideration to these points, it was decided to build a classical cyclotron. It was felt that such a machine has the advantage that while it is used as a source of particles for experiments with the external beam, such as accurate scattering experiments, it could also, without modification, be used as a versatile isotope producer to employ a number of experimental groups on studies in nuclear spectroscopy. There was also the possibility of utilizing it as a neutron source for neutron physics and biological experiments.

In deciding on the size of the cyclotron, much weight was given to the analysis of optimum size for fixed-frequency cyclotrons, given by M. S. Livingston¹). It was thus decided to design a cyclotron with a deuteron energy of 16 MeV.

2. The Magnet

In designing the magnet the first decision to be taken was to fix the gap width. It was known that the M.I.T. cyclotron had accelerated up to 1 mA of deuterons using a $5\frac{1}{2}$ inch gap, and that this intensity was found to be difficult to handle due to problems of heat removal. It thus appeared that very little would be gained by using a larger gap.

It was further decided to use a minimum quantity of high quality magnetic steel rather than a steel of indifferent quality, and at the

† Left the National Physical Research Laboratory in July 1956. Now at S. A. Philips Laboratories, Johannesburg.

same time to aim at a design that would give a maximum of experimental space around the vacuum chamber. These characteristics were

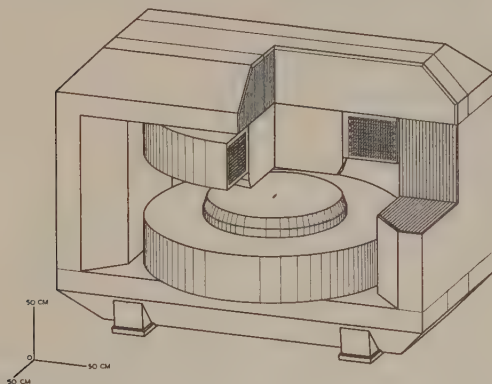


Fig. 1. Magnet construction.

possessed to an admirable degree by the magnet of the 225 cm cyclotron which the firm of ASEA of Västerås, Sweden, constructed for

the Stockholm magnet, adapted to the special needs of this cyclotron.

The general construction is shown in fig. 1. The yoke consists of 8 blocks, the heaviest being the two sides which weigh 10 tonnes each. Bevelling of the uprights adds considerably to the accessibility of the accelerating chamber. The yoke blocks were built up by welding together $1\frac{1}{4}$ inch rolled steel plates, whereas the two poles each consist of a solid forging. Pure, low carbon steel was used throughout and showed the following analysis: Carbon 0.08% maximum, silicon 0.27% maximum, manganese 0.37% maximum and other impurities negligible.

Every block was carefully machined to an accuracy of ± 0.001 " on all contact surfaces and the magnet was assembled without using shims of any description to obtain the necessary tolerance of 0.001" for parallelism of the pole faces.

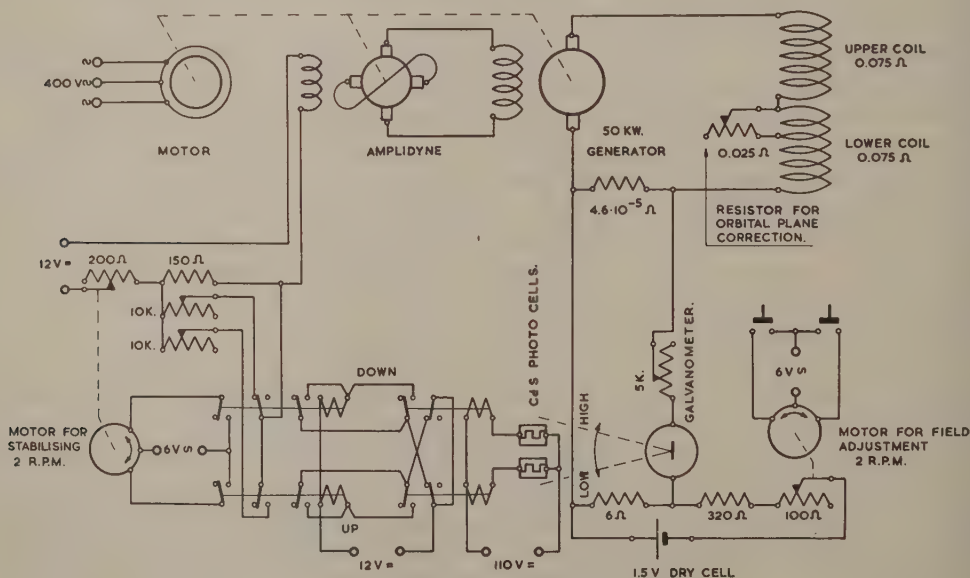


Fig. 2. Basic magnet circuit diagram.

Nobelinstitutet för Fysik in Stockholm. During the design stage of the magnet ASEA consented to Dr. Dreyfus acting as consultant, and the final magnet is basically a half-scale model of

The coils were wound with extruded aluminium conductor having a cross-section of 28×22 mm with a 10 mm diameter hole down the centre for cooling water. The aluminium

conductor was obtainable in continuous lengths of 705 feet, thus enabling a complete double pancake of 36 turns to be wound from a single length. Each coil consists of 6 double pancakes, giving a total of 432 turns per coil. The coil collars are made of the same low carbon steel as the yoke, and form part of the magnetic circuit.

The magnet is powered by an 80 kW motor-generator set directly coupled to an amplidyne exciter. This set can provide up to 700 amperes but 600 amperes is sufficient to reach the necessary field strength.

For stabilization, use was initially made of an

helical potentiometer gives the required correction in the amplidyne field current. Owing to the time constant of the magnet (22 sec), the reaction of this system would be far too slow to give proper stabilization. Therefore the amplidyne field coils receive an extra current pulse from the motor relays (marked UP and DOWN). This pulse only lasts until the error is corrected, i.e. when the light spot is back on the cells and the motor is switched off. In this way the magnet current is kept constant within 0.02% without any drift.

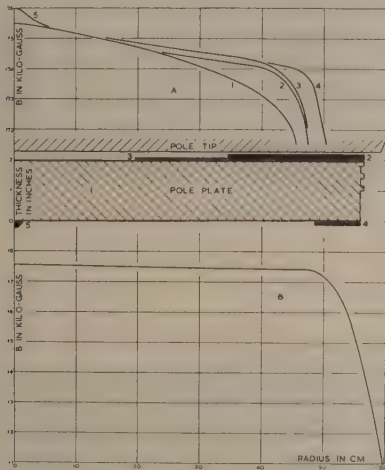


Fig. 3. The fringing field (B) and effect of shimming on the radial field plot (A).

instrument which compares the characteristics of a triode, placed in the fringing field, with those of an identical triode, placed in the field of a permanent magnet²). This apparatus proved to be very sensitive to RF pick-up and was eventually replaced by a conventional current stabilizer of the galvanometer type. The principle of the circuit is shown in fig. 2. The light spot normally covers two cadmium-sulphide photo-cells, which actuate a direction sensitive relay circuit. Finally, a motor-driven

²) C. A. J. Kritzing, "Die stabilisatie van die magneet-veld vir 'n 15 MeV-siklotron", M. Sc.-thesis, University of Pretoria (1955).

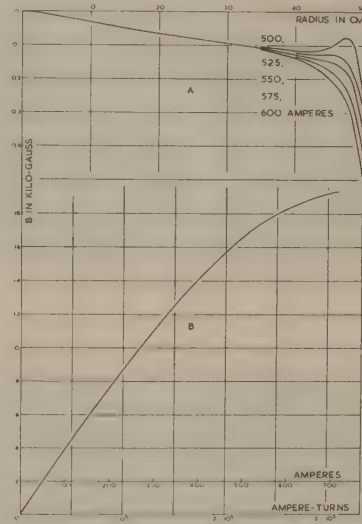


Fig. 4. Effect of the magnet current on the radial field plot (A) and magnetic field strength versus ampere-turns (B).

The two pole tips, which also form the lids of the vacuum chamber are 2" thick and were machined to a slightly conical shape, the height of the cone being 0.040". This was done in an effort to produce the necessary negative field gradient without using too many shims.

Fig. 3 shows how the required magnetic field curve was obtained. The field without shims is given by curve No. 1. With this field a beam of 60 μ A deuterons was accelerated to a radius of 45 cm. By adding the shims 2, 3, 4 and 5 the field was consecutively altered to that shown by curves 2, 3, 4 and 5 respectively. It will be noted that shim No. 4, placed inside the vacuum

chamber, gives an important contribution towards the required field curve. This shim was only put in reluctantly, however, as will be discussed later. With the ion source now in use, the cone, shim No. 5, did not have any effect on the beam current, and was consequently removed.

Curve B in Fig. 3 shows the fringing field. In Fig. 4 the curves A show the dependence of the field form on magnet current and curve B gives the field strength in the centre of the magnet as a function of the current.

uniformity which is not better than 1 in 3000 in the "flat" region of the field. The two pole tips will be replaced by new ones made of forged steel in the near future.

There can be little doubt that most of the difficulties encountered in getting fixed frequency cyclotrons to operate satisfactorily, are due to the magnetic orbital plane not coinciding with the geometrical median plane of the magnet. In our magnet the radius of curvature of the lines of force is of the order of 100 meters. It is

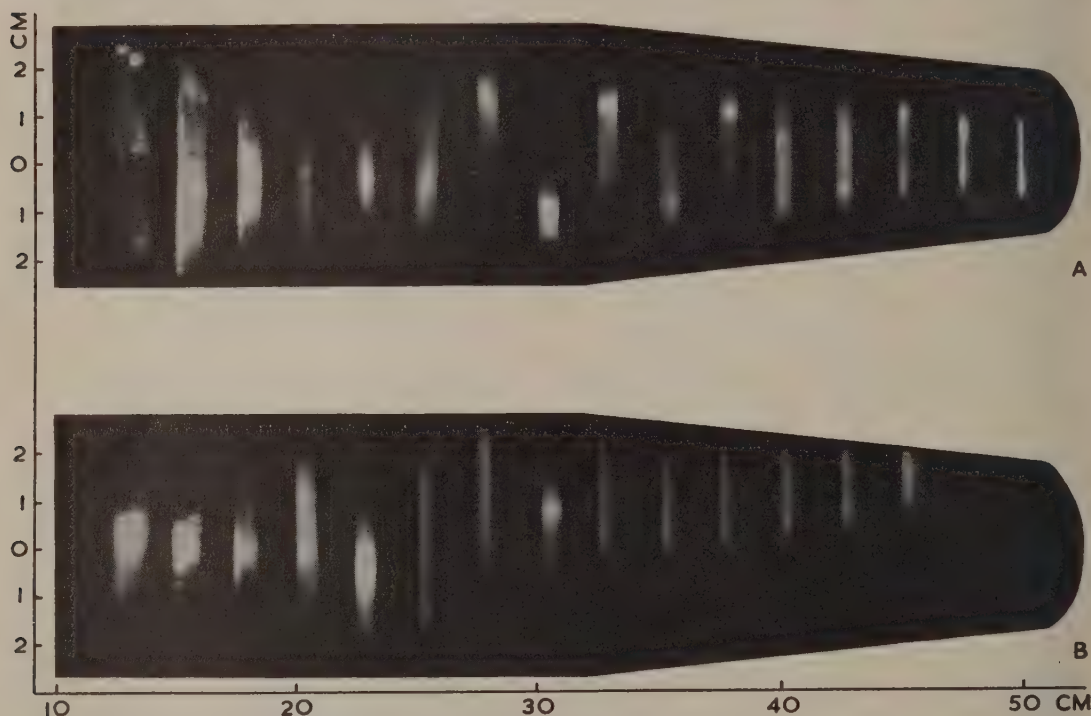


Fig. 5. Autoradiographs of beam: (A) with orbital plane resistor and (B) without.

Extensive measurements were done to check the field for azimuthal uniformity. Although very accurately machined, the pole tips introduced azimuthal inaccuracies of up to 25 gauss at a radius of 50 cm. This possibly originates from the fact that they were machined from rolled steel. Shimming to correct the azimuthal variations proved to be non-reproducible, and was eventually discarded, and at present the cyclotron operates with an azimuthal

obvious that very small irregularities in the shape, position and composition of the vacuum chamber lids or shims can cause considerable deviations.

The orbital plane was measured with the suspended wire method³). Without the pole plates the orbital plane coincides with the geometrical median plane to within 1 mm. When

³) Glen R. Lamberton, "Use of the wire loop in locating the orbital surface of a cyclotron field", U.C.R.L.-3366.

measured with the pole plates in position, the maximum deviation becomes 6 mm. With the original shimming in position (including those for azimuthal uniformity) the maximum deviations became as high as 30 mm and this caused a complete loss of beam at 35 cm radius.



Fig. 6. The magnet.

When this was realized, the cyclotron was run for some time without any internal shims, but to increase the beam intensity one internal peripheral shim (No. 4 of fig. 3) was necessary. Even this single shim caused a complete loss of beam, due to orbital plane errors, before the maximum radius was reached. This is shown in fig. 5, B, which shows autoradiographs of test targets irradiated for very short periods at various radii. By shunting the two upper "pancakes" of the lower coil by a 0.025 ohm resistor, the orbital plane could again be brought inside the dees. This is shown in fig. 5, A. It is obvious that the beam is still subject to fairly large vertical oscillations, and that there is scope for further improvement.

The completed magnet is shown in fig. 6. The cabinet to the right contains certain auxilliary equipment such as the ion source gas supply, the ion source voltage supply, vacuum gauge power supply etc.

3. The Vacuum System

The general lay-out of the cyclotron vacuum chamber, dee lines and vacuum system is

shown in figs. 7 and 8. The dee lines make an angle of 20 degrees with each other, and are large enough to enable the dees to be withdrawn from the cyclotron without dismantling the dee lines themselves. This has proved to be a valuable feature, as the dees can be run out on two fairly light cantilever trolleys running on the floor on ordinary rubber wheels.

Letting the dees diverge by 20 degrees has the advantage that a single diffusion pump can be used, and that it becomes possible to construct a high vacuum seal-off valve of very simple and straightforward design. From a radiofrequency point of view it has definite disadvantages however.

The mechanical pump was placed in a pit under floor level together with other auxilliary equipment such as water pumps, auxilliary vacuum pump and the D.C.-generator of the ion source.

The main volume to be evacuated consists of the two dee lines, made of $\frac{1}{4}$ " thick electrolytically pure non-arsenical copper, and the stainless steel vacuum chamber of which the top and bottom lids consist of the low carbon steel pole tips. The volume of the system, vacuum pumps excluded, is 2200 l.

Single rubber gaskets are used between all components; and have been designed so as to provide maximum accessibility for leak hunting with a helium leak detector. Only the pole tips have double gaskets, with provision for evacuating the space between them, as they are hard to get at and difficult to replace.

The flanges, valves, sliding and flexible seals used were standardised from the beginning, and are now used on all vacuum equipment in the Nuclear Physics Division. Some of these components are shown in fig. 9. In the case of the quarter swing valves the spindle, which has to be sealed on only one side, is made vacuum tight by means of a short piece of rubber tubing, sealed to the body of the valve on one side, and to the spindle on the other. During operation the tubing twists through 90 degrees.

The performance of the vacuum system is shown in fig. 10. The dashed curve is the

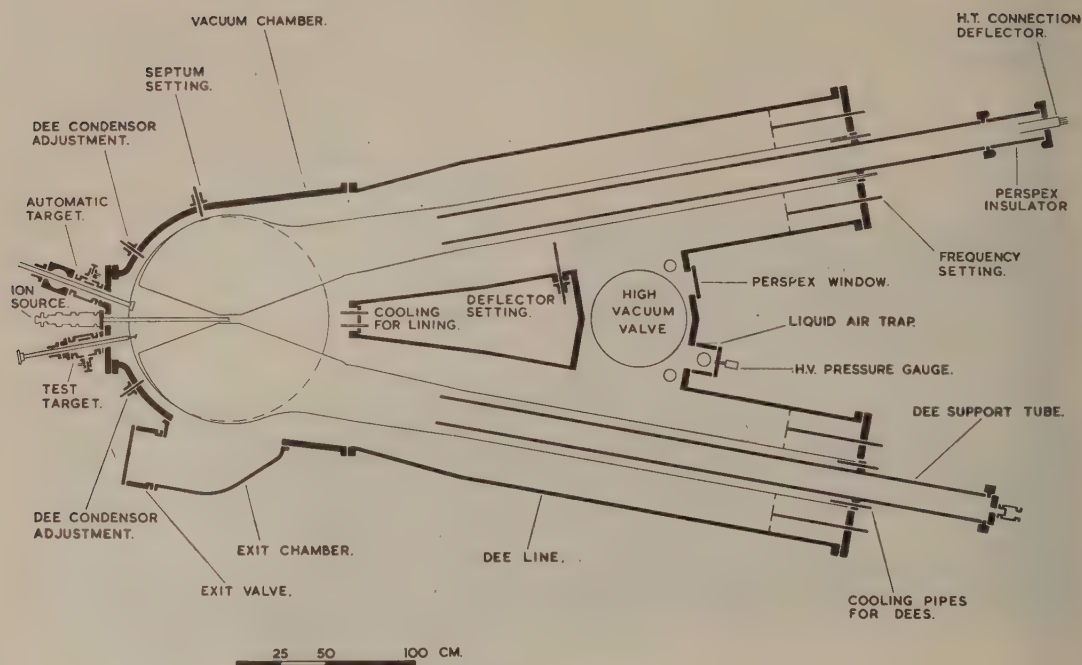


Fig. 7. The vacuum system: horizontal section.

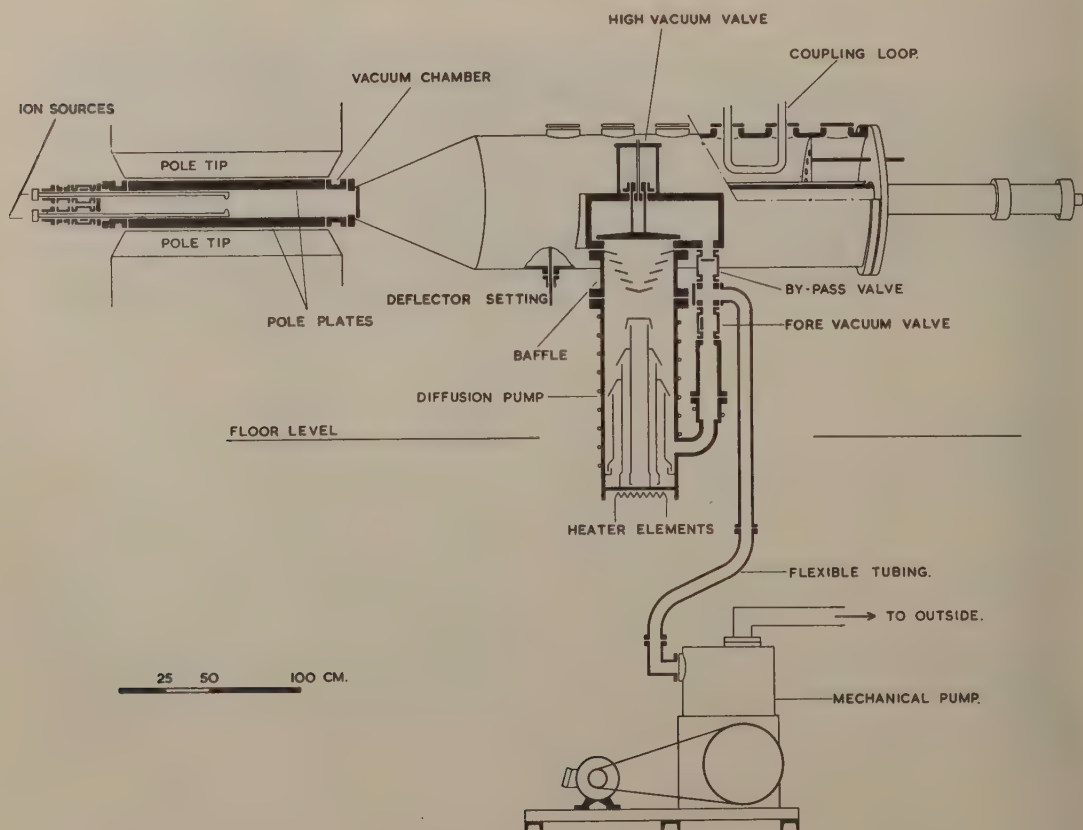


Fig. 8. The vacuum system: vertical section.

theoretical curve for the ideal case of no out-gassing. Curve B is the actual performance in the case where the cyclotron has been open to

which measures pressures from 10^{-7} to 5×10^{-1} mm Hg. It indicates either the high vacuum or the fore vacuum on both control panels simultaneously.

Control of the system is fool-proof. Valves and pumps can only be switched on and off in the correct sequence from either control panel, failure of the water cooling or of any of the seven heater elements is immediately indicated and in the case of power failure all valves close automatically. The high vacuum shut-off valve closes pneumatically in 0.2 second whenever the pressure in the system exceeds 0.3 mm Hg.

4. The Radiofrequency System

The design of the self-excited, tuned grid tuned plate oscillator is similar to the oscillators in use at the Massachusetts Institute of Technology and at the Universities of Pittsburgh and Illinois⁴). The basic diagram is shown in fig. 11.

The dee system is tuned to a frequency of 13.25 MHz. The dees and dee stems, adjustable in all directions, are made of copper and supported by stainless steel tubes to obtain the required mechanical strength. The dee lines are of solid copper, and the vacuum chamber has copper linings.

The construction of the short circuiting plates for the dee stems, used for rough tuning, is shown in fig. 12A. To ensure good all-round contact, these plates are fitted with fingers of soft copper which are each individually pressed on to the inside of the dee lines and the outside of the dee stems by shielded steel springs, each capable of exerting a force of 2.25 kg. In fig. 12B and C the contact between the vacuum chamber copper lining and the dee lines is shown. Good contact is ensured in this case by cutting the throat of the lining into fingers, that are quite soft, and pressing them very hard against the dee lines by means of the rubber gasket shown. The vacuum chamber lining consists of two parts, one fixed to the pole tips, and the other to

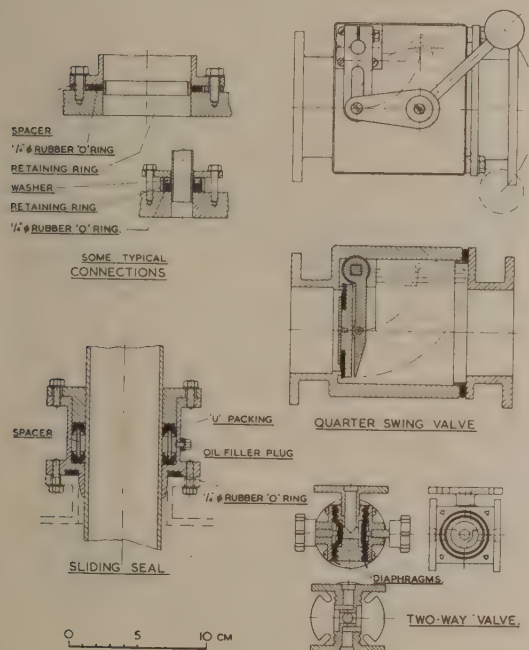


Fig. 9. Vacuum components.

the atmosphere for some time, and curve A shows the normal condition where the cyclotron has been standing under vacuum.

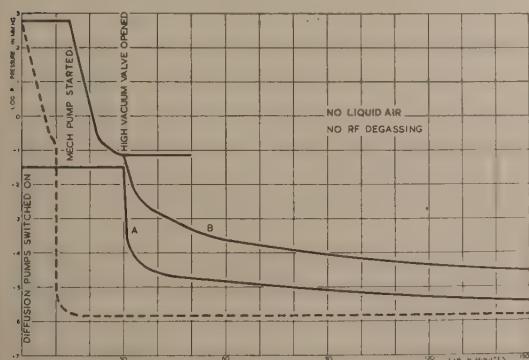


Fig. 10. Evacuation time curves.

The pressure is measured on a Distillation Products modified Philips Ionisation Gauge

⁴) G. F. Tape, University of Illinois Cyclotron Oscillator, Technical Report No. 1. Office of Naval Research, Task contract N6 ori-71 T.O.1.

the vacuum chamber. Contact is again made by flexible fingers.

Accurate tuning is obtained by varying the distance between the dees and the movable sides of the copper lining of the vacuum chamber.

thus cancelled out to a first approximation. The dee voltmeters were calibrated by measuring the energy of the X-rays coming from the dees with a hot filament inserted in the centre of the vacuum chamber. To calibrate each dee volt-

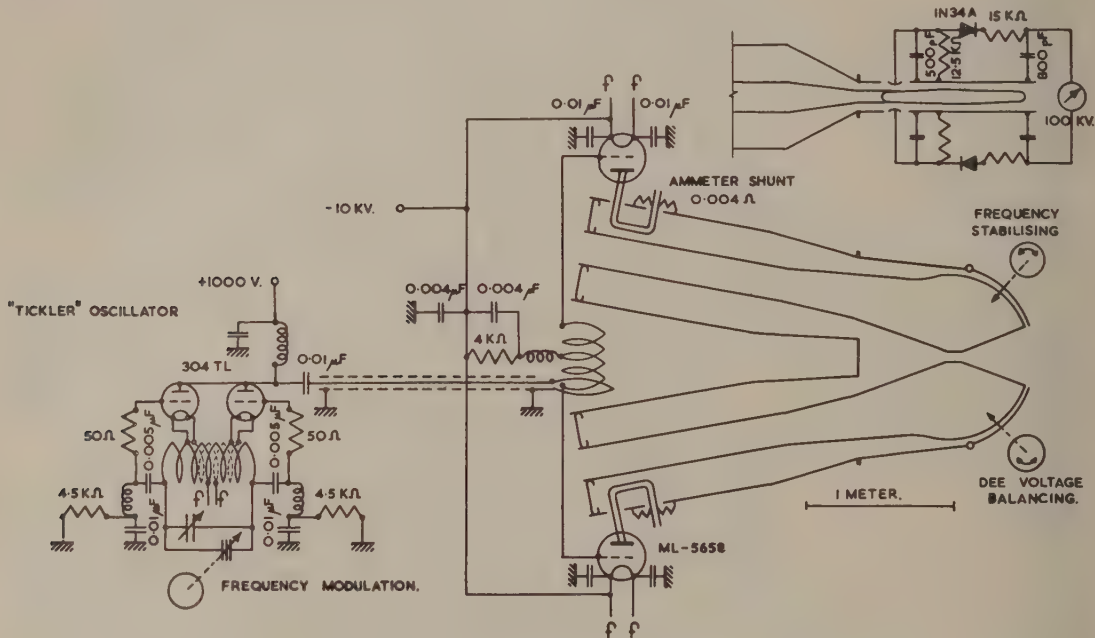


Fig. 11. Basic diagram of R.F. system.

This adjustment, which gives frequency changes of up to 1 percent, is motorised. This enables compensation for frequency changes, due to the normal thermal deformation of components, to be carried out by remote control while the cyclotron is in operation.

Two Machlett ML-5658 triodes are used as oscillators, coupled to the dee system by anode loops of approximately 1000 ohm impedance. Under no-load conditions the oscillator shows the following typical operating values: Anode voltage 7 kV, anode currents 1.27 A grid current 0.67 A and dee voltages 55 kV. The dee voltage pick-up electrodes are situated on both sides of both dees, being placed in positions where the dees are flat (see fig. 11 top right). Small changes in the position of the dees are

meter separately, the other dee was earthed, allowing only the dee under observation to oscillate.

The R.F. energy developed in the resonator system is 8.7 kW under the above conditions divided as follows: dees 10%, dee stems 56%, short circuiting plates 8%, dee lines 21% and vacuum chamber lining 5%. The Q of the system is about 7000.

To improve the starting of the oscillator a booster oscillator is coupled to the grid coil. This oscillator is of similar design to that of the 60" cyclotron at Berkeley⁵). The grid circuit of the booster is tuned to half the cyclotron frequency to prevent feed-back damage, and is

⁵) K. E. Relf, The Radio-frequency system of the 60" cyclotron at Berkeley, U.S.A.E.C.-BP-42 3rd Ed.

frequency modulated by means of a rotating capacitor. Once stable oscillation is reached the booster is switched off.

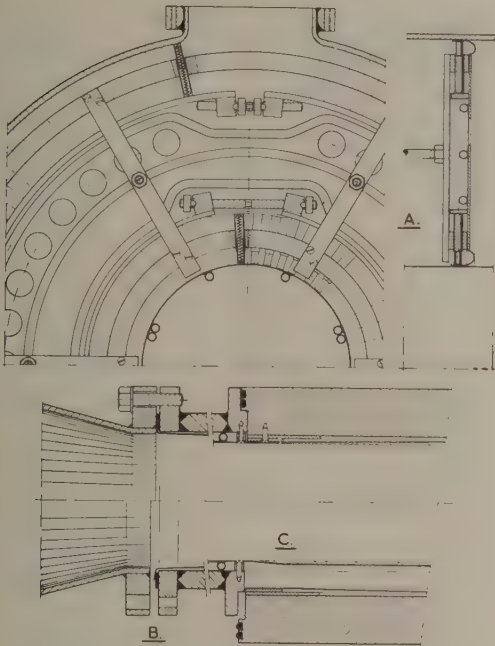


Fig. 12. R.F. connections.

5. The Ion Source

The ion source is of the conventional open type and is shown in fig. 13. As can be seen from the drawing, there are in fact two ion sources, used one at a time, while the other is used as the electron target. When a filament burns out, the functions of the two sources are interchanged by operating a switch on one of the control panels.

The U-type filaments are made of tungsten of 2 mm diameter and they vary in life-time from 30 to 60 hours. They can be replaced by removing the filament holder through an air lock. A D.C.-generator supplies 130 to 140 A for heating the filament to maintain an emission current of 2 to 3 A. The voltage between the filament and the cavity, made of a copper tungsten alloy, is between 200 and 400 V. An electron current of approximately 0.5 A strikes the opposite electron target.

The gas flow is supplied by an electrolysis cell and is regulated by an adjustable leak⁶⁾, which is basically a small cavity, alternately connected to the gas supply and to the ion source vacuum. The small valves that effect this, are driven by a variable speed motor. By varying and measuring the speed of the motor, the gas flow can be controlled and measured on the control panels. Gas flows of 0.02 to 0.03 mm³/s are used, causing a pressure in the ion source cavity of the order of 0.05 mm Hg. The same ion source is used for producing molecular hydrogen ions and alpha particles. In these cases the beam currents are approximately 20% lower than for deuterons.

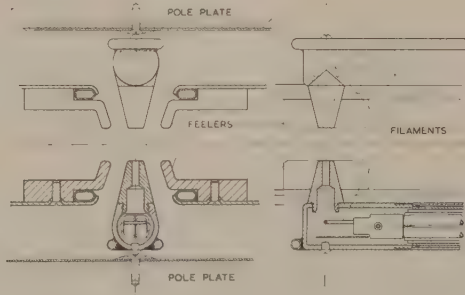


Fig. 13. The ion source.

6. The Control and Cooling Systems

An effort was made to make the control system as fool-proof as possible. A system of interlocks makes it impossible to switch on components in the wrong sequence. Above each switch or control is a set of three pilot lights, red, green and yellow. Circuits cleared for switching on, are indicated by the yellow light coming on, accompanied by the red light. As soon as the circuit is switched on, the green light replaces the red, and the next circuit cleared is indicated by its yellow and red lights coming on. This enables relatively untrained staff to operate the cyclotron without endangering the machine.

As the distance between the cyclotron hall and the control room is approximately 40 m, a second control cabinet was provided in the cyclotron hall itself to facilitate adjustments to

⁶⁾ J. J. Burgerjon, *Rev. Sci. Instr.* 25 (1954) 522.

the machine itself. It duplicates the control room panels shown in fig. 14 except for controls used only when the beam is circulating.

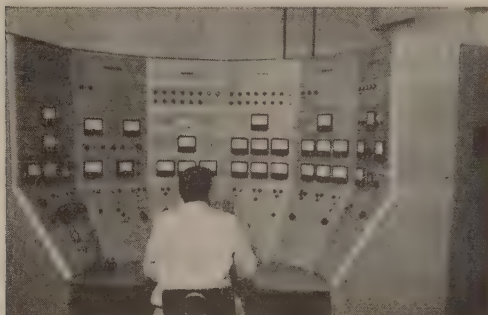


Fig. 14. The control console.

For reasons of safety the water filled doors, described later, can only be closed and opened on the spot. Their position is, however, shown on the control room panel and they interlock the ion source when open. With all cyclotron components switched on, the doors can no longer be opened from the outside. It is, however, always possible to open them from the inside in case somebody happens to be trapped in the cyclotron hall.

The control system works from a 12 volt D.C. supply, which consists of a three-phase selenium rectifier and stand-by battery, to maintain essential services in case of power failure. All relays are of the plug-in sealed type.

All components in which heat is developed, have flow switches on the exit side of their cooling circuits. These flow switches are interlocked with the respective control circuits, automatically switching off all components liable to damage if the cooling water fails in any specific circuit. The flow switches and all the valves of the cooling system are centralised on one side of the magnet in a lay-out that closely resembles an electrical switch board. Flow meters and thermometers are provided and can be switched into any of the 40 cooling circuits to facilitate the measurement of the heat developed in any component, especially those carrying R.F. The lay-out is shown in fig. 15.

All cooling circuits are part of a closed system

that circulates pure distilled water. The circulating centrifugal pump has a capacity of 390 l/s. The heated water circulates through

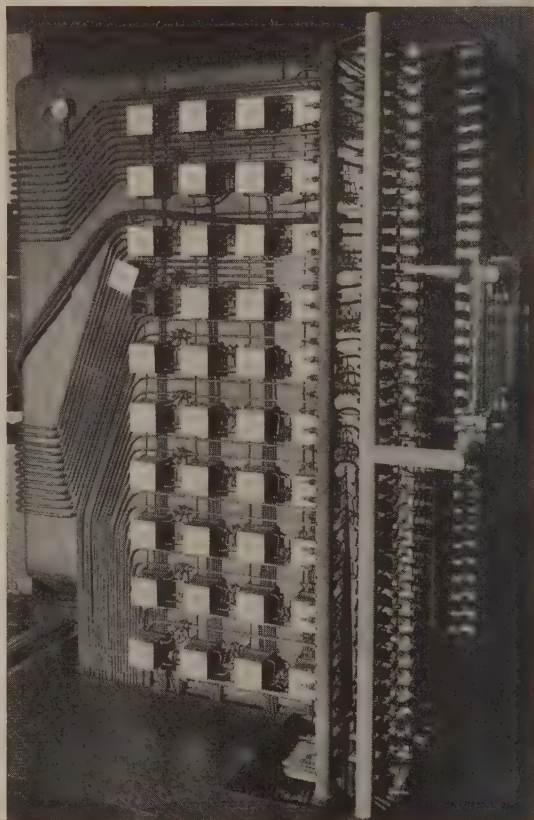


Fig. 15. The cooling "switch board".

copper tubes submerged in an open cooling pond. No inhibitor is used in the cooling water, and after 4 years of operation no noticeable corrosion has occurred in the aluminium magnet windings.

7. Targets

In fig. 7 two gates are shown through which targets can be inserted. One is used either for a probe target which can intercept the beam down to small radii, or for a hand operated target. The other gate is used for the automatic target.

Fig. 16 shows the calculated deuteron energy as a function of the radius at which the target is placed. The measured beam current at various

radii is also indicated. This was measured calorimetrically with the probe target, at constant dee voltage. The amount of heat developed in the target can be read continuously on the control panel by using thermocouples to measure the rise in temperature of the cooling water. As the rate of water flow usually changes after fitting a new target, push button calibration is provided by switching on two electric elements of known wattage and adjusting the meter deflection accordingly. The cooling water passes one element first, then the target and finally the other element, so that heat losses during the calibration are approximately the same as during actual operation.

The beam current is measured directly by a

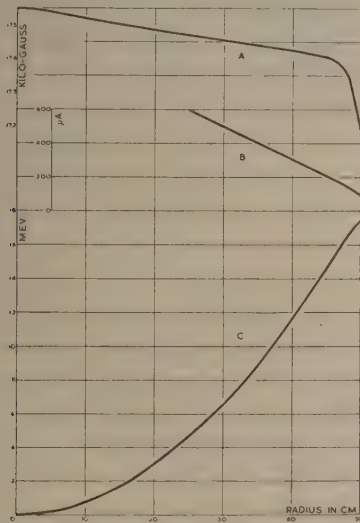


Fig. 16. The radial field (A) beam current versus radius (B) and deuteron energy versus radius (C).

beam indicator and integrator consisting of a D.C. amplifier with negative feed back and a capacitor, which actuates a preselecting counter to switch off the cyclotron. With this instrument, currents from 0.05 to 500 μ A can be measured and integrated while the target is maintained near earth potential. The beam current is also recorded on a calibrated recorder.

For handling highly active targets, an

automatic target removal and despatch mechanism was installed. When using this mechanism the operator presses a single button in the control room after completion of the irradiation. This sets off the following automatic sequence of events: The cooling water through the target is cut off, and at the same time the target support starts moving outwards through the sliding seal. The beam vanishes simultaneously because the ion source is interlocked with the target cooling water, and is switched off automatically when the flow is interrupted. In the meantime the target is connected to the compressed air supply, and any residual cooling water blown out. After the target has passed through the vacuum lock, the valve closes and air is admitted into the lock. The target is now pulled out completely, and a pair of shears, actuated by a falling weight, cuts through the copper tubes, dropping the target into the carrier of the

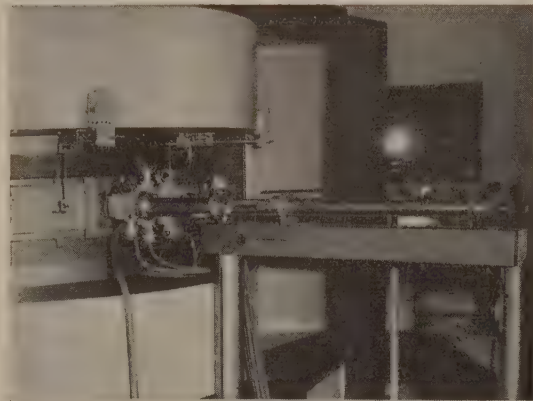


Fig. 17. The target extraction mechanism.

pneumatic tube system, already in position in its tube. The bottom of the container consists of two insulated conical halves. On touching these, the target closes a circuit which causes the lid of the container to close, and releases the carrier to be blown to a receiver behind a lead wall in the hot laboratory about 50 m away. From the instant the button is pressed until the target arrives in the laboratory takes 15 sec on the average. The mechanism is shown in fig. 17.

8. The Cyclotron Building

An excellent site was available for the Nuclear Physics Laboratory, which was to house the cyclotron as part of its equipment. The site consists of sandy soil, 10 m deep, resting on a layer of broken up diabase which goes down to 40 m. The water table is below 35 m.

the floor structure. In designing the hall the structural engineer worked on the assumption that if the whole hall were to be jacked up at two opposite corners, the cyclotron foundation should not distort by more than 0.03 mm.

Cyclotron components were lifted from trucks coming to the side of the building by a ten ton

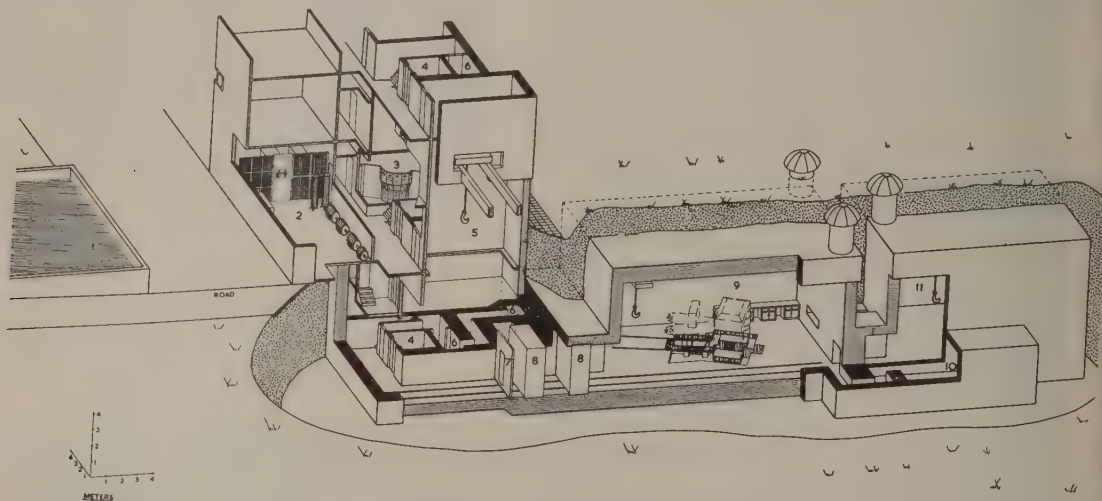


Fig. 18. The cyclotron building.

As the laboratory was being designed for nuclear spectroscopy, it was decided to have the machine as near to the main building as possible, while still providing adequate screening. The floor of the cyclotron hall was placed 9 m under the normal ground surface, and a minimum of 4 m of earth and concrete was provided as screening on any direct line between the cyclotron and the laboratory rooms.

A drawing of the cyclotron hall and part of the main building is shown in fig. 18. The cyclotron hall 9 is 6.5 m high with a 1 m reinforced concrete roof covered with 2.5 m of earth. The cyclotron magnet rests on two heavily reinforced concrete beams 80 cm wide by 3.5 m deep which form the sides of a machine pit and water reservoir, 12, under the magnet and dee lines. The ends of these beams are tied into two other beams, 3×1.3 m, which run from wall to wall, and form an integral part of

electric crane and lowered down the shaft, 5, to be pushed into the hall on a trolley running on tram rails. For screening purposes the corridor leading to the cyclotron hall, is sealed by two water filled steel tanks, each 1.25 m thick, weighing a total of 40 t. To reduce neutron leakage the doors, when closed, are still recessed 15 cm into the wall, ceiling and floor and project 30 cm into the recesses in the back wall. The movement is hydraulic.

The hall is kept dust free by electrostatic precipitators in the ventilation inlet. All services and control wiring pass along the maze, 6, to enter the cyclotron hall below floor level.

The control room, 3, is on the ground floor of the laboratory, and so is the machine room, 2, which houses the motor generator set for the magnet, the rectifier set for the oscillator and other equipment for the rest of the laboratory.

Room 11 is to be used for experiments with

the extracted cyclotron beam. The screening has proved to be excellent and no measurable radiation reaches any of the laboratories.

The completed cyclotron is shown in fig. 19.

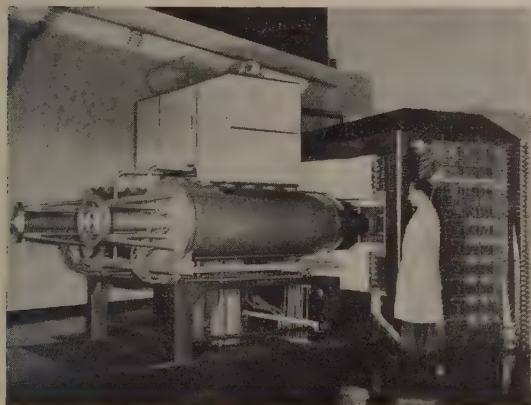


Fig. 19. The Pretoria cyclotron.

9. Technical Data

9.1. THE MAGNET

Weight of yoke (excluding pole pieces)	58.7 t
Weight of pole pieces	12.2 t
Weight of 2" pole tips	0.8 t
Weight of coils	7.5 t
Total weight	79.2 t
Steel analysis, carbon 0.08% max, silicon 0.27% max, manganese 0.37% max, phosphorus 0.006%, sulphur 0.026%.	
Shimming gaps	0.25"
Gap between vacuum chamber lids	5.5"
Coil windings 432 turns of 99.5% aluminium 22 × 28 mm with 10 mm diameter hole	
Working current	600 A
Working voltage	82.5 V
Time constant	22 s
Stability	0.02%.

9.2. THE VACUUM SYSTEM

Volume	2200 l
Ultimate vacuum	2×10^{-6} mm Hg
Working pressure	6×10^{-6} to 1.2×10^{-5} mm Hg
Leak rate	10^{-3} mm l/s
Gas flow	1 to 2% 10^{-2} mm l/s
Mechanical pump	42 l/s (Leybold S 150)
Oil used	Shell Vitrea
Diffusion pump	5000 l/s (C.V.C. MCF 5000)
Oil used	Octoil
Heater elements	3000 W (heating up 4220 W).

9.3. THE OSCILLATOR

Type	Tuned grid-tuned plate, self excited push-pull
Oscillator valves	Machlett ML-5658
Frequency	13.25 MHz
Anode voltage	7 kV
Anode currents (with beam)	1.84 A
Total grid current	0.67 A
Dee voltages	55 kV
Q	7000
Dee capacity	250 pF
Minimum dee to ground distance	26 mm
Efficiency	50% approximately
Anode supply	12 kV 150 kW
	Mercury arc rectifier.

10. Acknowledgements

During the initial stages of the design of the cyclotron two of the authors were privileged to spend a lengthy period at Nobelinstitutet för Fysik in Stockholm. We wish to thank Prof. Dr. Manne Siegbahn and his staff most cordially for the hospitality and friendship extended to us, and especially Prof. Dr. Kai Siegbahn and Dr. Hugo Atterling for their personal interest and advice. The help of Dr. Dreyfus of ASEA, with his wide experience of magnet design, was most valuable. Thanks are also due to Prof. Dr. M. S. Livingston for his personal interest in the project at the time the basic designs were being made.

We would like to thank Mr. Zaayer of S.A. Philips for his advice in connection with the R.F. system and Dr. W. R. McMurray for performing the dee voltage measurements by means of X-rays. Staff members of the Nuclear Physics Division and workshops who took part in the construction were Messrs. W. Weidemann, L. D. Bruins, Z. de Velde-Harsenhorst, L. Raavé, G. O'Grady and J. van der Walt. Their enthusiastic aid is sincerely appreciated, as well as that of Mr. J. van der Staay and the staff of the Central Workshops.

Finally it is a pleasure to thank the President of the South African Council for Scientific and Industrial Research and the Council itself for their interest in this project and for making it possible by supplying the necessary funds.

MULTIPLE FAST COINCIDENCE UNIT

KRISTIAN SKARSVÄG†

Nuclear Physics Research Laboratory, University of Liverpool

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A fast diode coincidence unit which can be driven by photomultiplier pulses is described. The coincidence circuit can be changed from a double to a triple or quadruple by a switch. A resolving time, τ , of about 3 μsec with

100% efficiency can be achieved. The dead time following non-coincident and coincident input pulses are about 16 and 70 μsec respectively.

1. Introduction

Millimicrosecond coincidence circuits are reviewed by Bell¹⁾ and Bay²⁾. Strauch has pointed out the most important requirements³⁾. The coincidence circuits may be conveniently classified into three types, parallel, series and bridge types⁴⁾. Double coincidence circuits of the parallel type⁴⁻⁹⁾ can most easily be adapted to multiple coincidence circuits^{10,11)}.

2. Design

A coincidence unit usually consists of limiters, clipping cables, a coincidence circuit, an amplifier and a discriminator (fig. 1). If a rising pulse is clipped, the length of the resulting pulse depends upon the rise time of the pulse and the electrical length of the clipping cable. The pulse is therefore limited before it is clipped. With the limiter in the photomultiplier box and the coincidence circuit on a different chassis the limiter anode load will be $Z_0/2$, where Z_0 is the characteristic impedance of the signal cable and the clipping cable. The modern photomultipliers such as RCA 6342 and RCA 6810A give anode pulses into a 130 ohm cable large enough to cut a limiter valve off. The limiter valve can thus be on the same chassis as the coincidence circuit, and the anode load can be nearly Z_0 . The coincidence circuit to be described here is a diode coincidence circuit of the parallel type^{12,13,14,9,15,11)}. It has, however, a clamping

diode and also a discriminating diode as in the coincidence circuit of Garwin¹⁰⁾. The main difference between his circuit and this is that the input triodes in his circuit are replaced by diodes. The uhf germanium diodes have very little stored charge¹⁰⁾, and are fast enough to be used as elements in a fast coincidence circuit. Their small size and small capacity to earth make them very convenient.

The limiter valve should be a sharp cut-off valve which can be run at a high steady current, and it should be a fast valve with small valve capacities. The pentode E180F and one half of the double triode E88CC are both found to be quite satisfactory. The signal cable is terminated by a 130 ohm resistor at the coincidence unit end. Due to the input capacity of the limiter

¹⁾ R. E. Bell, *Ann. Rev. Nuclear Sci.* **4** (1954) 93.

²⁾ Z. Bay, *Nucleonics* **14**, No. 4 (1956) 56.

³⁾ K. Strauch, *Rev. Sci. Instr.* **24** (1953) 283.

⁴⁾ Z. Bay and G. Papp, *Rev. Sci. Instr.* **19** (1948) 565.

⁵⁾ R. E. Bell and H. E. Petch, *Phys. Rev.* **76** (1949) 1409.

⁶⁾ R. E. Bell, R. L. Graham and H. E. Petch, *Can. J. Phys.* **30** (1952) 35.

⁷⁾ R. L. Garwin, *Rev. Sci. Instr.* **21** (1950) 569.

⁸⁾ K. P. Meyer, E. Baldinger and P. Huber, *Helv. Phys. Acta* **23** (1950) 121.

⁹⁾ S. De Benedetti and H. J. Richings, *Rev. Sci. Instr.* **23** (1952) 37.

¹⁰⁾ R. L. Garwin, *Rev. Sci. Instr.* **24** (1953) 618.

¹¹⁾ R. Madey, *Rev. Sci. Instr.* **26** (1955) 971.

¹²⁾ B. Howland, C. A. Schroeder and J. D. Shipman, Jr., *Rev. Sci. Instr.* **18** (1947) 551.

¹³⁾ T. C. Chen, *Proc. I.R.E.* **38** (1950) 511.

¹⁴⁾ W. C. Elmore, *Rev. Sci. Instr.* **21** (1950) 649.

¹⁵⁾ G. H. Minton, *Phys. Rev.* **94** (1954) 758; (see also ref. 2)).

† Now at the Joint Establishment for Nuclear Energy Research, Kjeller, Norway.

valve a small part of the photomultiplier pulse is reflected, but with E180F or E88CC as limiter valves this pulse reflection is negligible, and the signal cable need not be terminated at the photomultiplier end. The cathode current of the limiter valve is set by the cathode resistance and the negative supply voltage (with E180F 25 mA cathode current of which 20 mA is anode current, with E88CC 18 mA cathode current). The limiters are shielded from each other. Each limiter valve has a 130 ohm clipping cable in the anode circuit. The pulse reflected from the short circuited far end of the cable makes the resulting pulse negative at its back end. This negative pulse is limited by a uhf germanium diode GEX66.

All the n channels in a coincidence circuit are here assumed to be equal. I_a is the anode current of the limiter valves, R_a is the anode load of the limiter valves and ρ is the dynamical resistance of the input diodes (D_2 to D_5 in fig. 1). The standing current in the input diodes are partly fed from a resistor (R_{10}), I_1 , and partly from the clamping diodes (D_6 and D_7) in series with a resistor, I_2 . The discriminating diode, D_8 , is biased by the main part of the d-c voltage difference appearing across the clamping diodes, $B(I_2)$. If the n input pulses and the double electrical length of the clipping cables are long compared with the rise time of the coincidence pulse, we have approximately for the voltage changes at the anodes of the limiter valves, at the common junction of the diodes and at the input of the linear amplifier.

$$v_a = R_a I_a - R_a I_2/n \quad (1)$$

$$v_d = R_a I_a - (R_a + \rho) I_2/n \quad (2)$$

$$v_g = \frac{R_g}{\rho_d + R_g} (v_d - B(I_2)) \quad (3)$$

where R_g is the parallel resistance of R_{15} and R_{16} , and ρ_d is the forward resistance of the discriminating diode.

v_d and v_g are implicitly dependent upon I_1 through the value of ρ . It will be seen that v_g decreases nearly linearly with increasing I_2 .

For $n-1$ input pulses the change in the current

in the clamping diodes, $i(v_d)$, is related to the change in the voltage across the diode, v_d .

$$i(v_d) = \frac{1}{n} (n-1) (I_1 + I_2) - v_d \left(\frac{1}{R_{10}} + \frac{1}{R_a + \rho} \right), \quad (4)$$

$i(v_d)$ and v_d can be found from the current-voltage characteristics of the diode and eq. (4) (ρ is assumed to be constant). The bias of the discriminating diode, $B(I_2)$, is known, and the minimum value of I_2 for a definite value of I_1 can thus be found for the case that no pulses at the input of the linear amplifier are wanted. The appropriate value of I_1 for a given value of I_a can best be found experimentally. Optimal values of I_1 and I_2 for $I_a = 20$ mA are about

$$\begin{array}{ll} I_1 = 9 \text{ mA} & \text{and} \quad I_2 = 6 \text{ mA,} \\ 11 \text{ mA and } 16 \text{ mA} & \text{for } n = 2, 3 \text{ and } 4. \end{array}$$

This is a higher current than usually used in diode coincidence circuits. It makes the circuit more insensitive than usually for some extra stray capacity, and it was therefore possible to incorporate in the fast part of the circuit a switch which can change the circuit from a double to a triple or a quadruple coincidence circuit.

The coincidence pulse is stretched before it is amplified. With a GEX66 as a discriminating diode and a Z759 as an amplifier input valve (13pF input capacity) the decay time of the coincidence pulse is about 70 μ sec. The amplifier is a linear amplifier of conventional design with a gain of 50 and a rise time of 25 μ sec (from 10% to 90%). The discriminator trigger circuit is of the type designed by Collinge *et al.*¹⁶⁾. We note that the output pulse height is about the corresponding bias minus 6 volts.

3. Performance

The coincidence unit has been tested with pulses with a sharp rise and an exponential decay of 15 μ sec decay time (derived from a mercury-relay pulse generator) applied to the inputs of the coincidence unit. The height of the

¹⁶⁾ B. Collinge, A. W. Merrison and D. Eccleshall, J. Sci. Instr. 33 (1956) 72.

coincidence pulse increases linearly with the length of the clipping cable from 0.1 to 0.6 m and levels so off (1 m = 4.27 μsec). With 0.5 m clipping cable the height of the coincidence pulse increases from 4 to 20 volts when the height of the input pulses increases from 1 to 3 volts, and it is independent of the heights of the input pulses in one or more channels for input pulse heights larger than 3 volts. The size of the feed-through pulses is negligible. With the circuit connected for triple coincidences double feed-through gives an output pulse of 1 volt for input pulses of 30 volts. The curve giving the output pulse height (or the corresponding discriminator bias) as a function of the relative delay of the input channels can be used to define the resolving time. For a definite discriminator bias and a definite height of the input pulses the coincidence unit responds only to input pulses coincident within $\pm$ the half width of the curve at that bias, i.e. the resolving time τ for that bias and that height of the input pulses. The resolving time is a function of the discriminator bias and of the input pulse height. Provided the input pulses are larger than 3 volts, the resolving time is not very dependent upon input pulse height.

The dead time of the coincidence unit following non-coincident pulses is somewhat larger than the length of the input pulses. With 8.5 μsec rectangular input pulses and with a discriminator bias of 10 volts the dead time is 16 μsec . The dead time of the coincidence unit following coincident input pulses is 70 μsec at a bias of 10 volts.

The coincidence unit has been tested with a source for counting rates up to 2×10^5 coincidences/sec, and the dead time was found to be independent of the counting rate.

The unit has been tested with 382 MeV protons in a beam. The detectors were 3.3 MeV thick plastic scintillators mounted with light guides on RCA 6342 photomultipliers. The photomultipliers were run at a high tension of 1850 volts. The delay curves I, II and III, fig. 2 were recorded with 0.5 m clipping cables and a discriminator bias of 6, 8 and 12 volts. The

resolving time, τ , measured as the half width at half maximum is 4.0, 3.2 and 1.8 μsec respectively, and the efficiency is 100%, 100% (as indicated by the flat tops) and 97%. The separation time, defined as the smallest time interval between any two events not resulting in a coincidence, is 5.3, 4.6 and 3.2 μsec . Similar delay curves were recorded with the circuit connected for triple and quadruple coincidences.

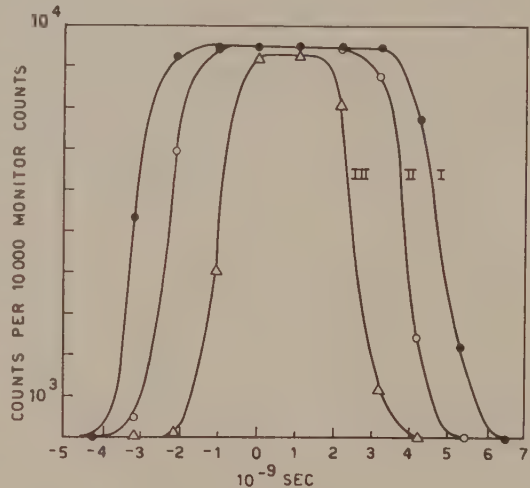


Fig. 2. Delay curves taken with 382 MeV protons. The curves I, II and III are with 6, 8 and 12 volts bias.

Two coincidence units of this type were used in the measurement of the spin correlation coefficient in proton-proton scattering, $c_{nn}^{17,18}$. During the main run the units were connected for triple coincidences with their outputs feeding a coincidence unit of resolving time $\tau = 25 \mu\text{sec}^{18}$. The sum of the single rates of the three counters feeding one coincidence unit was about 5000 counts/sec. With a mark to space ratio of 1 to 150 it corresponds to 7.5×10^5 counts/sec during the beam pulse.

¹⁷ K. Skarsvåg, Ph. D. Thesis, University of Liverpool (1957).

¹⁸ A. Ashmore, A. N. Diddens, G. B. Huxtable and K. Skarsvåg, Proc. Phys. Soc. 72 (1958) 289.

Acknowledgements

The author wishes to thank Professor H. W. B. Skinner for hospitality, and Dr. R. Jarvis who started this work with fast coincidence circuits. The author also acknowledges many valuable discussions with Mr. G. B. Huxtable and Mr. A. Ashmore. The author is indebted to the Royal Norwegian Council for Scientific and Industrial Research for a fellowship, and to the Joint Establishment for Nuclear Energy Research for leave of absence.

FUNCTION OF THE COLLECTING ELECTRODE IN A VAN DE GRAAFF GENERATOR

K. S. SUBUDHI

Department of Physics, Banaras Hindu University

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In the Van de Graaff electrostatic generator the electric charge at a high voltage is stored on a metallic collecting electrode. In 1933 Van de Graaff *et al.* stated that the spherical collecting electrode is similar to a Faraday's ice-pail. A new explanation of the generation of the high voltage in the above generator was presented in 1954 by Simon. It is based on a different fundamental principle, namely, the Volta's condensing electroscope principle. Simon concluded that if the spraying system is maintained at a constant potential, the collecting electrode will also attain a constant

potential, the magnitude of which will be proportional to that of the spraying system. The factor of proportionality does not depend on the capacity of the collecting electrode but depends on the height of the machine. The results of the experiments performed on a self-exciting generator of Becker type indicate that the voltage of the generator does not depend on the metallic sphere and the voltage is increased as the height is increased even though the same collecting system is used. This is qualitatively in accordance with the Simon's theory.

As early as 1860, Lord Kelvin constructed an electrical influence machine known as the water-dropping apparatus¹). The water drops falling from an earthed metallic can, under the influence of an electrified field plate, get themselves charged and when they fall into a deep insulated vessel the electric charge is completely transferred to it. Kelvin also devised a regenerative arrangement in which the collecting vessel is connected to the field plate so as to further its influencing action.

In 1872, Righi¹) designed a machine based on the above principle using an endless india-rubber tube with rings of copper wire wound on it at intervals for carrying electric charges. The tube is mounted on two pulleys, one of which is connected to the earth and the other is turned by a handle. A body with the small charge which is to be multiplied is held near the earth-connected pulley. Each carrier then enters a metallic sphere and is discharged by a contact spring. A large electric charge is found to be accumulated on the sphere.

Following the same principle, R. J. Van de Graaff²) developed in 1931 a high potential generator capable of a steady output. A 2.2 inch silk ribbon belt is rotated between two pulleys, one of which is driven by a motor and

the other is located inside a 24-inch (diameter) hollow copper sphere mounted on a 7-foot upright pyrex rod. The ascending surface of the belt is charged near the lower pulley by a brush discharge, maintained by a 10 000 volt transformer-kenetron set. The charge thus sprayed on the belt is conveyed to the centre of the sphere where it leaks from the belt to the collector which is connected to the sphere. A potential difference of 1 500 000 volts was observed between two such identical units generating opposite kinds of electricity.

The maximum potential to which the sphere could be charged can be determined by knowing the break-down electric field of the medium surrounding the sphere. If the medium is air at atmospheric pressure, then the limiting electric field is 30 000 volts/cm or 100 ESU. If r is the radius of the sphere in cm then its capacity is r ESU. If Q is the charge and V the potential in ESU, then

$$Q = rV.$$

The electric field

$$E = Q/r^2 = V/r,$$

OR

$$V = rE.$$

¹) John Gray, *Electrical Influence Machines* (Whittaker, London, 1890).

²) R. J. Van de Graaff, *Phys. Rev.* 38 (1931) 1919.

Therefore the break-down potential

$$= 100 \times r \text{ E.S.U.}$$

$$= 30\,000 \times r \text{ volts.}$$

In the Van de Graaff's machine described above the radius of each sphere is $12 \times 2.54 = 30.48$ cm. So the corresponding break-down potential is 914 400 volts. The limiting potential difference between the two identical units generating opposite charges is 1 828 800 volts, which is slightly more than the actual potential difference (1 500 000 volts) achieved. This led Van de Graaff and his coworkers of the Massachusetts Institute of Technology to think that the voltage attainable in this device is limited only by the corona break-down at the surface of the sphere³).

The explanation for the development of high potential in such an electrostatic generator was given by Van de Graaff *et al.* on the basis of Faraday's ice-pail principle³) (in a paper published in 1933). They stated, "Since the interior of the sphere is similar to the interior of a Faraday "ice-pail" the charge passes readily between the charged belt and the sphere, irrespective of the potential of the sphere. The voltage which is attainable in this device is limited only by the corona break-down at the surface of the spheres, which depends in a known manner upon their size and varies somewhat with the degree of smoothness of their surfaces".

From the above explanation it follows that (1) the collection of charge from the belt and its transference to the sphere or collecting electrode should take place inside the hollow collecting electrode, (2) the voltage attainable is a constant depending only on the size of the collecting electrode and the insulating supports and (3) the collecting electrode is responsible for the production of high voltage, i.e., without the collecting electrode the voltage cannot be raised.

Contradicting the ice-pail theory of Van de Graaff *et al.*, Simon⁴) gave a new theory in 1954 for the production of high voltage in a Van de Graaff machine. According to Simon,

Volta's condensing electroscope principle should be used as a basis for the explanation of the action of the above machine. In this machine work is done in moving the electric charge on the belt against the force of attraction due to the oppositely charged spraying system and also against the force of repulsion due to the similarly charged collecting electrode. This work appears as increased electrical potential and therefore the charge on the belt while at the top is already at a high potential which the collecting electrode shares. (This is similar to the increase of potential of the charge on the plate of a charged condenser when the distance between the plates is increased.) This, according to Simon, shows that the collecting electrode does not play the primary role in the process of increasing the potential and that even if the collecting electrode is removed altogether the charge on the belt could be raised to a high potential due to the work done in moving it against the force of attraction of the spraying system.

Simon has developed a rigorous quantitative theory of a simple two carrier constant potential electrostatic generator and extended it to the Van de Graaff generator. He has shown that if the spraying system is maintained at a constant potential, the collecting electrode will also attain a constant potential, the magnitude of which will be proportional to that of the spraying system. The factor of proportionality does not depend on the capacity of the collecting electrode but depends only on the geometry of the machine (e.g., the height). According to this theory there is a maximum limit for the voltage of the collecting electrode even if all the losses of charge due to corona break-down and leakage are prevented, whereas Van de Graaff *et al.* supposed that in such a case the collecting electrode could be charged to an infinite potential.

However, if the potential of the collecting

³) R. J. Van de Graaff, K. T. Compton and L. C. van Atta, *Phys. Rev.* **43** (1933) 149.

⁴) A. W. Simon, *American Journal of Physics* **22** (1954) 318.

electrode, which is the product of the potential of the spraying system and the factor of proportionality given by Simon's theory, exceeds the break-down potential, then obviously the break-down potential sets the maximum limit. Therefore it is essential that the size of the collecting electrode should be large so that the break-down potential lies above the potential obtainable according to Simon's theory.

The author⁶⁾ has constructed a self-exciting generator following the modification of Becker⁶⁾. Its collecting electrode is a copper vessel having a diameter of 45 cm and a height of 35 cm. Four ebonite rods, each of length 90 cm and diameter 4.0 cm, have been used as the insulating columns. The belt has been made out of a rubber sheet of width 10 cm and thickness about 1 mm. The voltages have been measured reliably with a generating voltmeter constructed by the author following the principle of Harnwell and Van Voorhis⁷⁾.

The voltage of the generator has been found to be 200 kV. When the collecting electrode is removed completely it has been observed that the voltage developed is the same 200 kV. This shows that collecting electrode is not responsible for the production and development of high voltage in such a generator. This does not favour the ice-pail proposition of Van de Graaff *et al.* but is in accordance with the Simon's theory, which states that the voltage obtainable

does not depend on the capacity of the collecting electrode. It may be mentioned that in the above experiment when the vessel, acting as a collecting electrode of large capacity, is removed the upper pulleys themselves behave as the collecting electrode of small capacity.

Further, when the height of the insulating column is raised by 30 cm, the voltage of the generator is increased to 250 kV, even though the same collecting system is used. This can be understood from the Simon's theory according to which the voltage obtainable is inversely proportional to the coefficient of induction between the collecting electrode and the spraying corona blade. As the height of the insulating column is increased the coefficient of induction between the collecting electrode and the spraying corona blade decreases and hence the voltage of the generator increases.

The collecting electrode is usually a big sphere. Though the sphere is not required for the development of the high voltages in a belt generator, yet it would be useful for storing large amount of charge at that voltage and keeping the break-down voltage greater than the expected voltage attainable according to Simon's theory. The function of the collecting electrode is therefore stressed here not as one that develops a high voltage but as one that retains a high voltage.

The author wishes to thank Dr. B. Dasanacharya for his supervision and useful discussion. The author is also indebted to Messers A. Srinivasa Rao and M. V. Ramana Rao for their kind assistance in carrying out the work.

⁵⁾ K. S. Subudhi, Journal of Scientific Research of the B.H.U., Vol. 8 (1) (1957-58) 11.

⁶⁾ E. W. Becker, Z. Naturforschung 2a (1947) 395.

⁷⁾ G. P. Harnwell and S. N. Van Voorhis, Rev. Sci. Instr. 4 (1933) 540.

HIGH SPEED COUNTER CHRONOMETER

A. M. HILLAS† and R. M. TENNENT

The University of Leeds

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A counter chronometer is described which measures time intervals up to 12.75 microseconds by counting the oscillations of a 20 Mc/s free-running oscillator with a scaler. Provision is made for resetting the scaler by a fast pulse if

the measurement is not to be recorded. The scaler is based on conventional pentodes and germanium diodes, the high counting speed being attained by limiting voltage changes.

1. Introduction

In a recent experiment¹⁾ the mean lifetimes of negatively-charged muons which had been brought to rest in different materials were measured. This paper describes the counter chronometer developed to perform the actual time measurements. It is capable of measuring time intervals up to 12.75×10^{-8} s in steps of 5×10^{-8} s.

The principle of the counter chronometer is as follows: pulses derived from an oscillator of known frequency are fed into a scaler via a gating circuit. The start of the interval to be measured is marked by a pulse which opens the gate allowing the oscillator pulses to reach the scaler. The end of the interval is marked by another pulse which closes the gate and the scaler is left with a count which is related to the time interval to be measured. A short discussion of the requirements of a timer for cosmic-ray experiments will emphasize the advantages of the counter chronometer.

In any experiment in which cosmic rays are used as the source of ionising particles it is necessary to have a more-or-less complicated selection scheme to ensure that the appropriate particle is being investigated. Further, as the events occur randomly spaced in time, automatic recording is an advantage and often a necessity. It is therefore essential to have some method of

storing information until the selection scheme is satisfied and the automatic recording has taken place. There are two main approaches to this problem. In the first, the actual measurements are held up until the selection scheme is satisfied whereas in the second, the measurements are made very frequently (according to the requirements of a crude selection scheme) and stored until the full selection scheme has decided whether the event is genuine or not. Only if the event is genuine is the stored measurement recorded.

In the above-mentioned case of the measurements of muon lifetimes using cosmic rays, the selection scheme depended on the action of geiger counters while the timing measurements were on pulses derived from scintillation counters. It was not therefore desirable to delay the timing pulses while the relatively slow selection scheme operated and a timing system capable of storing information was sought for. Various timing techniques capable of storing information have been described²⁻⁶⁾ and of

¹⁾ A. M. Hillas, W. B. Gilboy and R. M. Tennent, *Phil. Mag.* 26 (1958) 109.

²⁾ S. H. Neddermeyer, E. J. Althaus, W. Allison and E. R. Schatz, *Rev. Sci. Instr.* 18 (1947) 488.

³⁾ J. W. Keuffel, F. B. Harrison, T. N. K. Godfrey and G. T. Reynolds, *Phys. Rev.* 87 (1952) 942.

⁴⁾ J. W. Keuffel, Princeton University Report No. 15 (1954).

⁵⁾ W. H. Bliss, *Electronics* 20 (Nov. 1947) 126.

⁶⁾ W. Weber, C. W. Johnstone and L. Cranberg, *Rev. Sci. Instr.* 27 (1956) 166.

† Now at the Atomic Energy Research Establishment, Harwell.

these, the most important for accurate work are the chronotron invented by Neddermeyer²⁾ and developed by Keuffel and his co-workers^{3,4)} and the counter chronometer⁵⁾. Recently a review of timing techniques in the nanosecond region has been given by de Waard⁷⁾.

The disadvantage of the chronotron for the muon lifetime experiment was that the wide range of mean lifetimes to be measured (1.5×10^{-8} s to 2.2×10^{-6} s) would have necessitated a correspondingly wide range of artificial delay lines. The counter chronometer on the other hand seemed ideally suited for the purpose. Provided that the scaler is capable of counting very rapidly and can record a high count, the same counter chronometer can cover a very wide range. It has the further advantages that by using a quartz-crystal-controlled oscillator, calibration troubles can be avoided; and that scaler counts can be easily photographed and translated back from the film into times.

At the time the experiment was planned, there were not any scalers available to count at the frequency required. Accordingly, a scaler

was developed capable of counting pulses occurring at frequencies up to 25 Mc/s and this scaler was connected to a 20 Mc/s quartz-controlled oscillator to form a counter chronometer. Although several authors⁸⁻¹⁰⁾ have referred to scalers of comparable speed, the present authors know of only one published faster scaler circuit¹¹⁾ and therefore believe that this instrument may be of interest.

2. The Instrument

2.1. GENERAL

Fig. 1 shows a block diagram of the counter chronometer. The instrument measures the time interval between the pulses applied to inputs 1 and 2. The trigger circuit, which is an ancillary piece of equipment, incorporates two separate fast discriminators and pulse-forming circuits fed by the two inputs. The discriminators, which use secondary emission pentodes type EFP 60, are similar to that described by Lewis and Wells¹²⁾ and produce pulses which rise to their maximum heights within 15 ns[†] of the start of the initiating pulses. The trigger circuit thus ensures that suitable pulses are fed to the gating circuit; the counter chronometer, in fact, measures the length of the pulse formed by mixing the two output pulses from the trigger circuit. As the two outputs are generated

- ⁷⁾ H. de Waard, *Nuclear Instruments* 2 (1958) 73.
⁸⁾ N. F. Moody, W. D. Howell, W. J. Battell and R. H. Taplin, *Rev. Sci. Instr.* 22 (1951) 439.
⁹⁾ J. Fischer and J. Marshall, reported by R. E. Bell, *Ann. Rev. Nucl. Sci.* 4 (1954) 93.
¹⁰⁾ H. K. Schoenwetter, *Rev. Sci. Instr.* 24 (1953) 515.
¹¹⁾ M. Nakamura, *Rev. Sci. Instr.* 28 (1957) 1015.
¹²⁾ I. A. D. Lewis and F. H. Wells, *Millimicrosecond Pulse Techniques* (Pergamon Press, London, 1954) 232.

[†] The abbreviations ms, μ s and ns will be used for 10^{-3} , 10^{-6} and 10^{-9} s respectively.

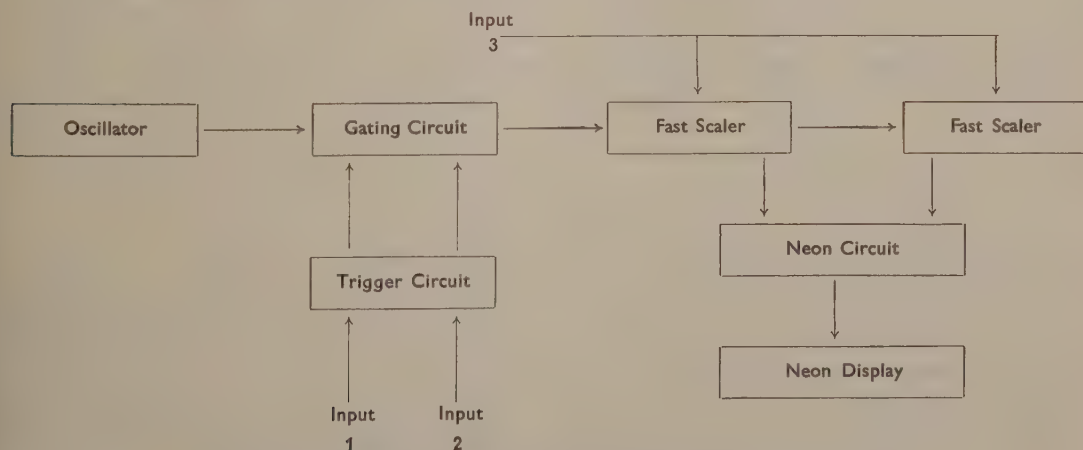
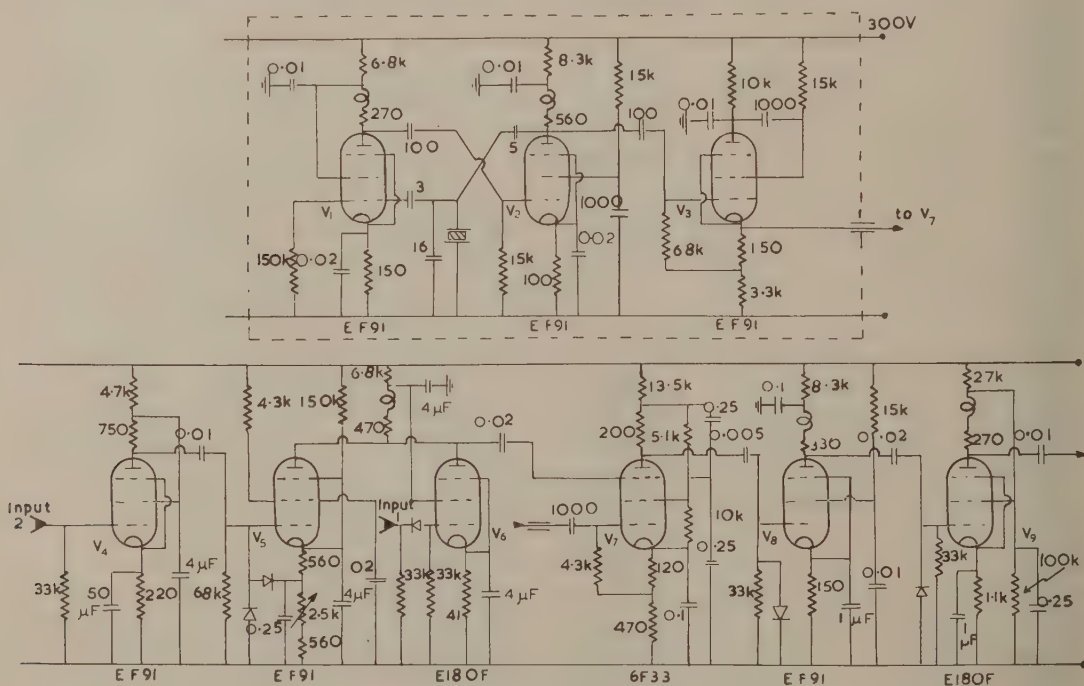


Fig. 1. Block diagram of electronic circuits used in the counter chronometer.

independently the pulse formed by mixing them has sharp front and back edges. To ensure linearity of the time scale down to the shortest time intervals, input 2 passes through a fixed delay before reaching the trigger circuit. With this precaution the front and back edges of the gating pulse do not overlap (i.e. the gating pulse attains its full size) even when the two signals originate from the same event. However, as this means that zero time interval leads to a count on the scaler, this effect must be allowed for when analysing results.

A paralysis is included in the circuits leading to input 1 to make certain that once a measure-

number of pulses which pass through a given gate may vary by one, depending on the phasing. This effect might be a disadvantage in experiments where the time intervals to be measured are of the same order as the separation of the oscillator pulses and the distribution of times not exponential. To avoid distortion of exponential distributions however, it is only necessary to ensure that the "zero" of time chosen is later than the true time at which the first event took place. This can be done by taking the "zero" of the time measurements as the next count after the larger of the two possible counts produced by simultaneous pulses at both inputs.



detail. The last four scales-of-two are conventional, since the separation of the pulses entering the fifth scale-of-two is $0.8 \mu\text{s}$ and special techniques are not required.

The basic fast scale-of-two is shown in fig. 3. Input pulses from the circuit shown in fig. 2 are negative, 15 V. The necessary speed of operation is obtained by using peaking coils in the anode circuit and by severely limiting the voltage changes occurring when the scale is triggered, a method which has been employed by Moody *et al.*⁷⁾ and Schoenwetter⁹⁾. If V_2 in the diagram is conducting, the crystal diodes which are shaded black are also conducting. The change in anode voltage on triggering is equal to the voltage across R (about 13 V). Crystal diodes are also used to prevent the grids being driven any further negative than is necessary, with a potentiometer to control the permitted potential change. With the circuit set in this way for maximum sensitivity it is necessary for the two sides of the scale-of-two to be well balanced: to achieve this, the resistors used are high stability

unduly affecting the speed or balance of the scale-of-two. However, as the voltage changes occurring in the circuit are small, indicator devices cannot be operated directly, and considerable amplification is required. Valves V_3 and V_4 amplify the voltage swings on the screen grids to operate a neon indicator circuit. It was found that reliable operation could only be obtained if interstage amplifiers were used to provide well formed pulses for the input to succeeding scales-of-two. The circuit of the first of these is shown in fig. 4; succeeding interstage amplifiers were slightly simplified versions of that shown.

Originally the four fast scales-of-two were identical, but it was found necessary to make minor alterations to each scaler circuit to obtain the best performance. These adjustments almost certainly arise on account of the difficulty in obtaining really satisfactory input pulses to each stage. The first stage (which receives the highest frequency input) has given little if any trouble as the input pulses are so narrow. Fig. 3 therefore

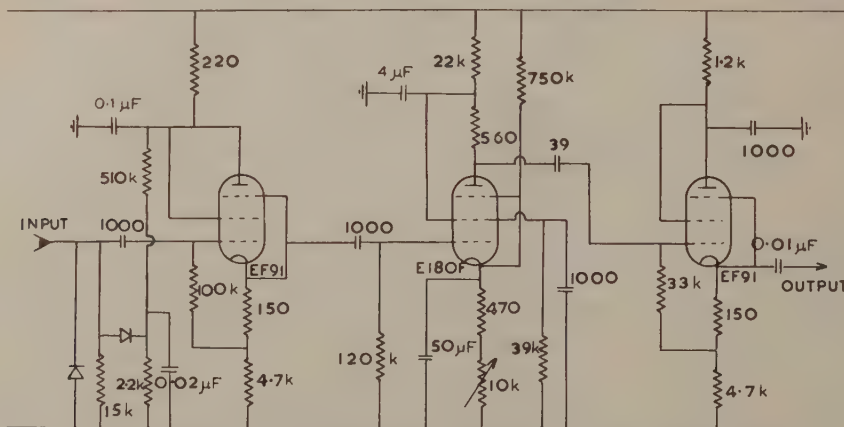


Fig. 4. Circuit diagram of the first interstage amplifier. All crystal diodes are type 0A71.

type of 1% tolerance and a potentiometer balance adjustment is provided. Pairs of valves are selected which have similar characteristics under the working conditions.

A further advantage of the use of pentode valves is that, if small screen resistors are used, signals can be taken from the screens without

shows the actual circuit of the basic scale-of-two and the components differing in the different scales-of-two are indicated by letters with the appropriate values shown in the table.

The scaler is reset to zero by applying a 30 V negative pulse $10 \mu\text{s}$ wide to input 3 (see also fig. 1) which is common to all units. When an

event is rejected, the selection circuits send the resetting pulses less than 50 μ sec after the event and it is found that the neon indicator lamps do not strike. The camera, which is not fitted with a shutter, does not therefore produce any record of unwanted results.

The adjustment of the scaler is carried out stage by stage. With insufficient limiting of the grid potentials, the scaler will not count fast enough, but with the limiting too severe the circuit becomes unstable. If the circuit needs balancing, the scaler tends to favour one state (e.g. V_1 carrying current rather than V_2), or will not count. When the first stage has been adjusted, with each potentiometer set in the middle of the range which gives satisfactory operation, the second stage is adjusted. Particular care is necessary to see that large odd and even counts are both counted correctly, and that when the total count is a multiple of 4, the second scale-of-two counts correctly. In use, such adjustment lasted until the ageing effects of the valves became sufficiently serious to cause trouble. With continuous use, the adjustment lasts a month or more; in fact, the whole scaler was tested very frequently during the muon lifetime experiment.

2.4. TESTING

The counter chronometer is tested by feeding two suitable pulses, generated by a test, double-pulse generator, into the inputs 1 and 2 of the trigger circuit. The separation of the pulses can be adjusted so that the scaler count varies over its whole range. Resetting pulses are also generated by the pulse generator but arranged to occur about 3 ms after the test pulses. With this long delay, the neon lamps strike, and the chronometer count can be observed as the neon lamps flicker with the repetition frequency of the pulse generator which is usually about 10 per second.

When the muon lifetime experiments were in progress, the pulse generator was sometimes set at a much faster rate, but the selection circuits were arranged to reset the scaler unless the

pulse from the pulse generator happened to be coincident with a pulse from a tray of Geiger counters. This test procedure simulated the experimental conditions extremely well and was found to be a very powerful check on the behaviour of the counter chronometer.

The counter chronometer has been in use now for more than two years. Its performance has been reliable. A simple pulsed oscillator was built up to check the performance at higher frequencies and it was found that counting was satisfactory at 25 Mc/s. There was no reason to suppose that it would not count at higher frequencies still.

2.5. RECORDING

The neon indicator lamps are arranged in a camera box and when an event is recorded, they are slightly displaced by a solenoid before being photographed. This is a precaution so that if for any reason a lamp were to come on at a time not associated with a "genuine" event, this fault could be detected by an image in the wrong place on the film.

It is found that the events are easily read from a film. Usually, the times are plotted directly on to a histogram using 50 ns channels. An observer can read film at a rate of 600 events per hour.

3. Conclusion

The 20 Mc/s counter chronometer described here has proved a reliable and convenient instrument for measuring time intervals in the range 5×10^{-8} s to 12.75×10^{-6} s.

4. Acknowledgements

It is a pleasure to thank Professor J. G. Wilson for his encouragement and Mr. W. B. Gilboy for help in running the counter chronometer and building a multiple pulse generator for testing purposes. One of us (A.M.H.) is indebted to the Department of Scientific and Industrial Research for a maintenance award during the course of this work.

CHARGE-STORAGE PULSE-HEIGHT ANALYZERS FOR USE WITH PULSED ACCELERATORS†

L. COSTRELL and R. E. BRUECKMANN

National Bureau of Standards, Washington 25, D.C.

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Storage type pulse-height analyzers for use with low duty cycle pulsed accelerators are discussed and an analyzer described that accommodates up to nine pulses in a single burst with a resolution of two microseconds. The pulses to be analyzed are temporarily stored as lines of charge on

the face of a cathode ray tube and are analyzed by means of an electron beam that detects the charge discontinuity at the peak of the pulse. The pulse-height information is then permanently stored in a magnetic core memory.

The low duty cycles of pulsed high energy accelerators makes the accumulation of energy spectrum data quite slow unless the machines are operated at very high pulse rates during their active periods. The high cost of operation of such accelerators plus the heavy demands made for time on the machines places a premium on their efficient utilization. Since the duty cycle is frequently of the order of 1 percent and, often as low as 0.1 percent, efficient operation necessitates pulse spacings not exceeding a few microseconds and preferably less than a microsecond. Analysis of such closely spaced pulses with reasonable efficiency and without pile-up error requires short time resolution and fast pulses.

The only existing multi-channel pulse height

analyzers that approach the desired time resolution are the "stacked" discriminator types such as those so highly developed by the Oak Ridge National Laboratories (Bell and Kelly^{1,2}) and the Gray wedge analyzers introduced by Maeder^{3,4} and refined by laboratories in the United States^{5,6,7} and Canada⁸). The high speed and simplicity of the gray wedge analyzer make this instrument attractive though it is limited to semi-quantitative measurements¹). Since the "stacked" discriminator analyzers, which were the first multichannel type analyzers to see wide use, are burdened by numerous high-speed discriminators, the trend lately has been toward the "pulse height to time conversion" type analyzers^{1,2,9,10}) first developed by

† This work was supported by the U. S. Atomic Energy Commission.

¹) G. G. Kelley, Methods of Pulse Analysis, International Conference on the Peaceful Uses of Atomic Energy, Paper A/Conf. 8/P166, June 18 (1955).

²) H. W. Koch and R. W. Johnston, Multichannel Pulse Height Analyzers, National Academy of Science, National Research Council Publication No. 467 (1957). (Proceedings of Conference at Gatlinburg, Tenn., Sept. 26-28, 1956).

³) D. Maeder, Electrophren-Spectrograph Zur Messung von Ionizations-Kammerimpulser, *Helv. Phys. Acta* 20 (1947) 139.

⁴) D. Maeder, Photographic Recording Methods in Nuclear Spectrometry, *Nuclear Instruments* 2 (1958) 299.

⁵) W. Bernstein, R. L. Chase and A. W. Schardt, Gray Wedge Pulse Height Analysis, *Rev. Sci. Inst.* 24 (1953) 437.

⁶) A. W. Schardt, Gray Wedge Pulse Height Analysis (Part 2), Brookhaven National Lab. Report, BNL 237 (Jan. 1954).

⁷) R. L. Chase, Coincidence Gray Wedge Pulse Height Analyzer, Brookhaven National Lab. Report, BNL 263 (Nov. 1953).

⁸) J. T. Flynn and F. A. Johnson, Fast Gray Wedge Analyzer for High Input Rates, *Rev. Sci. Inst.* 28 (1957) 867.

⁹) P. W. Byington and C. W. Johnstone, Los Alamos Scientific Laboratory Report, A 100 Channel Pulse Height Analyzer Using Magnetic Core Storage (1955).

¹⁰) R. W. Schumann and J. P. McMahon, Argonne 256 Channel Pulse Height Analyzer, *Rev. Sci. Inst.* 27 (1956) 675.

Wilkinson¹¹), feeding magnetic core storage arrays. The Wilkinson type analyzer has many advantages but high speed is not one of its virtues, especially when one is interested in microsecond and fractional microsecond resolution.

The trend toward the "pulse height to time conversion" analyzers has been spurred by the improved speed of magnetic core storage devices permitting resolution times of the order of 100 μ sec. Another factor that has accelerated this trend has been the wide acceptance of the philosophy that microsecond resolution is not as important as had been widely believed *provided* pile-up errors and spectrum bias are avoided. The "stacked" discriminator analyzer of Kelley and Bell uses an interrogation circuit that permits acceptance of pulses only if their separation from other pulses is adequate to avoid pile-up error. The "pulse-height to time conversion" analyzers refuse admittance to pulses that occur while a preceeding pulse is being analyzed[†]. Thus, these analyzers avoid distortion of the spectrum at high pulse rates even though the counting efficiency is low. With the development of the "pulse-height to time conversion" analyzers with relative freedom from spectrum distortion but with far poorer time resolution than that of their predecessors, the need for fast resolution has been reevaluated. As a consequence, it is generally recognized that the high resolutions formerly desired are not necessary and that the permissible counting rates of these "pulse-height to time conversion" analyzers with resolution times of the order of 100 μ sec is adequate for the majority of applications.

In the case of pulsed accelerators, resolution times considerably shorter than those obtainable with conventional "pulse-height to time conversion" analyzers are necessary for efficient operation. For example, a synchrotron with a burst rate of 60 per second and a 100 μ sec burst duration has a duty-cycle of only $\frac{1}{3}$ percent. If

the analyzer used to analyze the output pulses occurring in the bursts has a resolution exceeding 100 μ sec, the total pulse rate analyzed cannot exceed 60 per second and the pulse rate in channels of interest may be only a small fraction of a count per second. To approach an average analyzed pulse rate of one per burst where only a single pulse per burst can be accepted for analysis requires operating at several pulses per burst where counting loss is high and pile-up might be serious. Therefore unless the circuitry is such as to exclude pulses subject to pile-up, operation will usually be at a fraction of a pulse per burst. Operation at total pulse rates between 10^2 and 10^3 per second, which is certainly desirable from the standpoint of economical accumulation of data, requires analysis of several pulses per burst.

Cunningham¹²) first suggested that advantage be taken of the relatively long deadtime available between bursts in pulsed accelerators for leisurely analysis of pulses occurring during the bursts. He stored a pulse on the face of a cathode-ray tube and analyzed the stored pulse while awaiting the next burst. Cunningham demonstrated the feasibility of the technique though he limited his analysis to one pulse per burst.

Reaves^{2,13}) proposed a modification to this system using a raster type reading sweep so as to analyze several pulses per burst. Since the number of sweeps in his system is equal to the number of channels, the time allotted to each sweep becomes small for an analyzer with a large number of channels. For each stored pulse an output signal is routed to the memory every time the sweep raster detects the presence of the stored pulse. Thus a pulse whose peak lies in the one-hundredth channel will provide 100 output signals to the memory. The output is thus

¹¹) D. H. Wilkinson, A Stable 99 Channel Pulse Height Analyzer for Slow Counting, Proc. Cambridge Phil. Soc. 46 (1950) 508.

¹²) J. A. Cunningham, A Multi-channel Pulse Height Analyzer Using a CR Storage Tube, National Bureau of Standards Report NBS-3258 (1954).

¹³) J. H. Reaves, Speed of Analogue Electrostatic Storage, Nuclear Instruments 2 (1958) 136.

[†] To decrease the effective resolution time, the Pacific-Electro-Nuclear Corp. analyzer that is based on the Los Alamos design of Johnstone and Byington temporarily stores one pulse that occurs while a preceeding pulse is being analyzed.

inherently integral though it can, of course, be reduced to differential form by the use of proper circuitry.

In the charge-storage analyzer developed by the authors the pulses are applied to one of the vertical deflection plates of a cathode-ray tube during the accelerator burst and the beam is stepped horizontally by a staircase voltage generator, spacing the pulses evenly over the tube face. A ramp sweep is applied to the second vertical plate and the pulse height is read off by sweeping the beam vertically until a capacitive pick-up plate on the face of the tube detects the charge discontinuity presented by the top of the pulse. The analyze sweep gates "on" a channel designating oscillator which routes the pulse into the proper channel as in a conventional "pulse-height to time conversion" analyzer. A magnetic core memory is being used. The speed limitations of the "pulse height to time conversion" system are of no great concern here since the conversion takes place during the accelerator deadtime†.

The analyze sweeps are stepped horizontally by the same staircase voltage generator used during the "store" intervals. The number of analyze sweeps is therefore determined by the maximum number of pulses that can be analyzed per burst rather than by the number of channels, and is considerably less than in the raster sweep system. In addition, the output is differential, as desired.

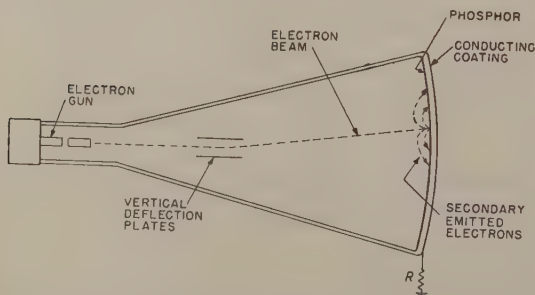


Fig. 1. Cathode-ray tube used as charge storage type pulse height analyzer.

† A paper on work being done at Yale University on a charge-storage type analyzer was presented by G. F. Pieper in September 1958 at the International Symposium on Nuclear Electronics, U.N.E.S.C.O. House, Paris, France.

The principle of operation is basically the same for all of the various charge storage systems described in this article. Pulses are applied during the "store" interval to the vertical

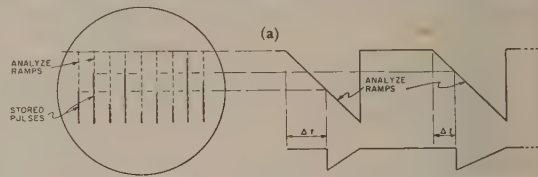


Fig. 2. Charge storage system showing storage and analysis of nine pulses. The analyze ramp detects the charge discontinuity at the top of the stored pulse. The time interval Δt is a linear measure of the amplitude of the stored pulse; a short interval corresponding to a high amplitude pulse and a long interval to a low amplitude pulse.

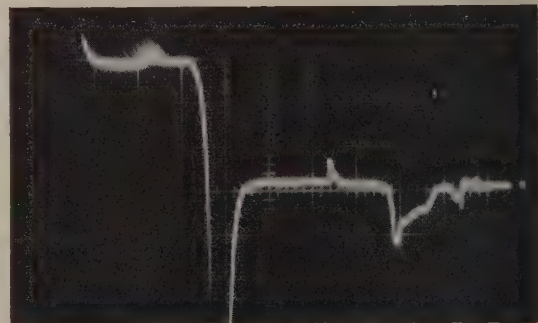
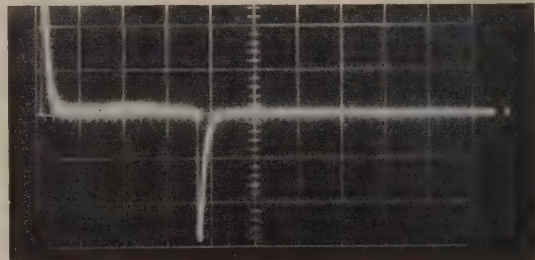


Fig. 3. Pick-up plate output. Sweep speed 50 $\mu\text{sec}/\text{cm}$ sensitivity 0.3 V/cm upper trace; 7 mV/cm lower trace. The large pulses at the beginning of the trace and at 180 μsec are due to the beginning and end of the store gate. The small pulses between 70 and 110 μsec are pulses being stored. The pulse at 320 μsec marks the beginning at the pick-up plate amplifier gate. (The analyze ramp starts 6 μsec prior to this pulse.) The signal output pulse is at 390 sec.

deflection plates of a cathode ray tube as shown in fig. 1, deflecting the electron beam accordingly. As the electron beam travels along the phosphor it ejects secondary electrons leaving a "line" of charge on the phosphor. A conducting coating

of the CRT. The pulse thus sweeps the beam vertically up the CRT face, storing charge on the phosphor. A store step pulse from the linear gate then steps the staircase voltage generator (fig. 8) the output of which (fig. 9) is applied to the horizontal deflection plates of the

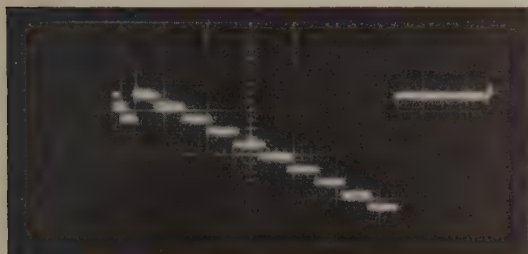


Fig. 9. Output of staircase voltage generator.

CRT. This steps the beam horizontally so that the next pulse to be analyzed is stored parallel to and displaced horizontally from the pulse that precedes it. The staircase generator utilizes a 10 position beam switching tube, resetting on the 10th position. There are thus 9 positions available for storing pulses so that the capacity of the analyzer is presently 9 pulses per burst. Fig. 2 shows 9 pulses stored on the CRT.

About 150 μ sec after the store gate is turned off the "analyze" period begins. The analyze gate produces "ramp initiate" pulses that pass several cycles of the 2 Mc/sec oscillator output to a scale of two that starts the analyze ramp (fig. 10) synchronous with the oscillator. This

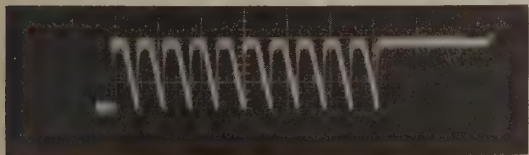


Fig. 10. Analyze ramp.

is shown in the magnified insert of fig. 7. The analyze ramp reads down to the top of the pulse as shown in fig. 2. When it detects the top of the pulse an output signal is obtained from the pick-up plate†. This signal is amplified and shaped by the pick-up plate amplifier, which gates "off" the 2 Mc/sec oscillator. Each cycle of the 2

Mc/sec oscillator represents a channel. Thus if 100 cycles are obtained before the pick-up plate output signal indicates detection of the top of the pulse, one count is added to channel number 100. Upon completion of the first analyze ramp, the staircase voltage steps one position so that the second ramp is in position to read the second pulse. Thus as each analyze ramp is completed the staircase generator displaces the ramp horizontally so as to permit it to read out the next pulse.

The maximum time required for each complete cycle of operation is 4200 microseconds (see fig. 7). This permits use of the analyzer with accelerator burst rates as high as 180 per second. (The NBS betatron operates at 180 bursts per second and the NBS synchrotron at 60 bursts per second.)

The magnetic core memory of a 256 channel analyzer has been used as the permanent memory. This was done for two reasons:

1. A magnetic core memory is well suited to the application.
2. It was a simple matter to plug into the memory of the available 256 channel analyzer without disturbing the internal wiring.

It is necessary to synchronize the read ramp with the 2 Mc/sec oscillator or a one channel uncertainty will result in the pulse sorting. The fast scale of two preceding the ramp generating circuit requires two of the 2 Mc/sec cycles to begin the ramp. This avoids synchronizing on a fraction of a cycle. The number of pulses that can be handled per burst is determined by the capacity of the staircase generator. The heart of the staircase generator is a 10 position beam switching tube in which the tenth position is used for reset purposes. This leaves 9 positions available for pulse storage. The staircase generator is reset by the closing of the store gate. Should 9 pulses arrive for storage prior to the normal closure of the store gate, the staircase generator blocks the stepping pulse and beam

† The pick-up-plate, prepared by Albert Krinsky of the National Bureau of Standards, consists of a 1/16" lucite disc on which a semitransparent layer of nickel has been evaporated.

intensifier circuits, excluding additional pulses that may apply for analysis during that particular store-analyze cycle. If the store time were not prematurely terminated in this manner, the staircase generator would repeat its cycle after the 10th pulse, writing new pulses over the pulses already stored on the CRT. Since the analyze ramp responds to the top of the stored pulses when scanning the tube face, it would detect only the highest of two or more superimposed pulses. This bias in favor of high pulses is eliminated by disabling the beam intensifier circuit after 9 pulses have been stored and keeping it disabled until the next regularly scheduled store is due.

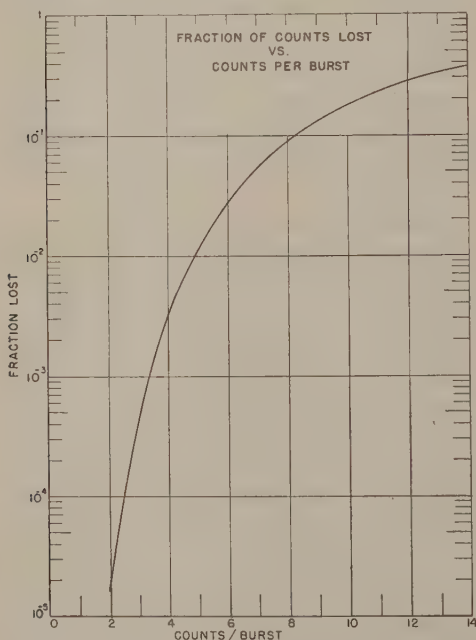


Fig. 11. Pulses "lost" due to nine pulses per burst capacity.

A question naturally arises as to why a store capacity of 9 was selected and what the effect of this limited capacity will be. As mentioned earlier, the 9 storage bins are those remaining after allotting one step of a 10 step beam switching tube to provide reset pulses. With the addition of a little additional circuitry, the 10th step could have been salvaged for store purposes while still performing its reset func-

tions. Also, the use of an additional beam switching tube in the staircase circuit would provide for storage of more pulses. Fig. 11 shows the fraction of the total pulses that are lost to the analyzer as a function of the average number of pulses per burst received by the analyzer. At an average pulse rate of 5 per burst, the loss, is only about 1 percent. Since this pulse rate is entirely adequate in our case, there was no point in providing greater storage capacity. The maximum burst duration with which we are concerned is about 1000 microseconds. Since the analyzer resolution is about two microseconds, the loss due to this resolution is again about 1% for a maximum duration burst and a pulse rate of 5 per burst. This is consistent with the 1% loss resulting from the limited storage capacity of 9 pulses per burst.

Fig. 11 was calculated as follows: The probability that a burst will contain x pulses when the average number of pulses per burst is n is given by the expression

$$p(x, n) = e^{-n} \frac{n^x}{x!}.$$

If a maximum of nine pulses can be accepted in any one burst, the number of pulses rejected by the analyzer because of this limited capacity will be:

$$\text{number lost} = \sum_{x=10}^{\infty} [(x-9) p(x, n)]$$

and the fraction lost is

$$\sum_{x=10}^{\infty} \frac{[(x-9) p(x, n)]}{n}.$$

This summation is more readily made by converting to the equivalent expression

$$\left\{ n - \left[\sum_{x=10}^{\infty} [x p(x, n)] + 9 \left(1 - \sum_{x=10}^{\infty} p(x, n) \right) \right] \right\} \frac{1}{n}.$$

As pointed out earlier, the ramp reads down until it detects the top of a stored pulse. It is therefore desirable that no stored pulses be of such amplitude as to terminate above the beginning of the ramp, line (a) in fig. 2. This means that high amplitude pulses should be uniformly clipped or saturation limited to fall

within a narrow region. If the channel determining 2 Mc/sec oscillator starts when the ramp is at (a), (fig. 2) channels between (a) and the pulse saturation level are not available for storage. For this reason it is advisable to limit this region. However, from the standpoint of linearity, an improvement is obtained by keeping this interval sufficient to discard the initial part of the analyze ramp. If desired, the channel space that would be lost at the beginning of the ramp could be salvaged by using a 2 Mc/sec scaling circuit between the oscillator output and the core memory circuit. Since the core memory that we used had 256 channels we had no hesitancy in discarding 26 channels and ending up with a 230 channel analyzer. One is reluctant to discard channels corresponding to low pulses since this limits the dynamic range but because of the fact that the analyze ramp starts above the stored pulse and sweeps down to it, channels discarded at the beginning of the ramp correspond to high amplitude pulses, above the saturation level.

Fig. 12 shows a cesium-137 spectrum taken with the analyzer using an RCA type 6810A photomultiplier tube and a 2" $\times$ 2" NaI(Tl) crystal. The pulse decay time was 0.5 μ sec and the pulse amplitude corresponding to the 662

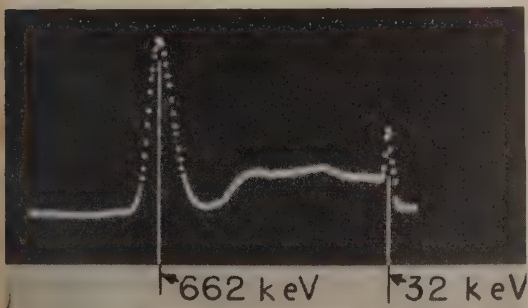


Fig. 12. Cesium-137 spectrum taken with charge storage analyzer. The 32 keV barium X-ray peak is at the right.

keV cesium peak was 60 volts. The 32 keV barium X-ray peak is at the right. Since no accelerator was used in obtaining this spectrum, 60 cycle pulses were used for the "start of burst" input. A store-gate duration of 200 microseconds

was used with a pulse rate of approximately 1.5 per burst.

Fig. 13 is a spectrum obtained from a DuMont type 6292 photomultiplier with a NaI(Tl) crystal

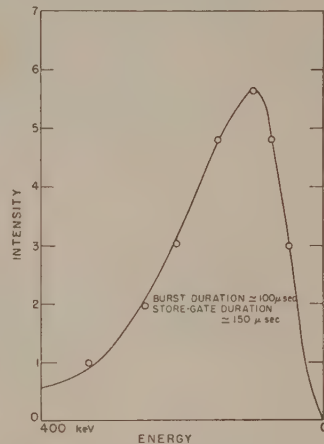


Fig. 13. Spectrum of scattered radiation from synchrotron beam taken with charge-storage analyzer. The solid curve was taken at 5.6 pulses per burst. The crosses represent data taken at one pulse per burst, normalized at the peak for comparison with the solid curve.

exposed to scattered radiation from a synchrotron operating at 60 bursts per second. The average pulse rate per burst was 5.6, the burst duration about 100 μ sec, and the store-gate duration about 150 μ sec. The circles show the same spectrum taken at an average rate of one pulse per burst and normalized at the peak for comparison with the curve obtained at the higher rate. The analyzer was also operated at 120 pulses per burst with a 50 μ sec burst duration. Since this corresponds to a pulse rate of 2.4×10^6 per second, the pulse pile-up was considerable.

The circuits that limit the resolution of the analyzer to the two microsecond value mentioned earlier are the staircase voltage generator and the linear gate. Since the speed of both of these circuits can be increased, this limit is not a fundamental one. Because of the slow speed of response of sodium iodide crystals, a resolution of one to two microseconds is about the best that can be fully utilized with NaI(Tl) scintillation spectrometers. However, fractional micro-

second resolution can be effectively utilized with spectrometers using fast scintillators. In order to reduce pile-up effects to acceptable values, the pulse width should not exceed 20 to 25 percent of the resolution time. This requires fast linear gates and stabilized non-overloading linear amplifiers. In order to investigate the feasibility of eliminating the amplifier and the linear gate, we have operated with high current

14 stage photomultiplier tubes feeding directly into the analyzer while gating on the apperature grid of the PMT. There are some difficulties associated with this mode of operation that require further investigation. The prototype that has been tested has not been thoroughly engineered. An engineered model is currently being constructed and will be subjected to extensive tests.

LETTER TO THE EDITOR

A NUCLEAR METHOD FOR DETERMINING
VERY LOW VAPOR PRESSURES

MOSTAFA F. AMR EL-SAYED

Department of Chemistry, Florida State University, Tallahassee, Florida

Received 1 November 1958

In recent years, Wolfgang and his co-workers¹⁻⁴) have succeeded in labeling organic compounds using the momentum properties of tritons formed in nuclear events. For solids and liquids, they used the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction; whereas, in gases, they used the ${}^3\text{He}(n,p){}^3\text{H}$ reaction^{5,6}). They obtained fairly good specific activities (0.2 millicurie/g in the case of CH_4 and C_2H_6). Even more recently, Wilzbach⁷) found that he could label organic compounds by simply sealing about 1 gram of the compound with a few cubic cm of tritium gas and allowing the system to stand at a normal or slightly elevated temperature for three to ten days. Fairly high tritium concentrations were obtained (e.g. in millicurie/g, 1.3 in heptane, 4.3 in sucrose, 22 in toluene, 125 in digitoxin). Such activity levels are 10^5 - 10^7 times greater than that required for satisfactory analysis.

The purpose of this note is to propose a method for determining the vapor pressure of compounds after they have been labeled by either of the above methods. Previous methods that have been used for determining vapor pressures are limited in accuracy for those compounds that

have a relatively low vapor pressure at the temperature of the measurement. If a method is designed using counting techniques, an unusual low vapor pressure determination is intrinsically possible, using tritium labeled compounds.

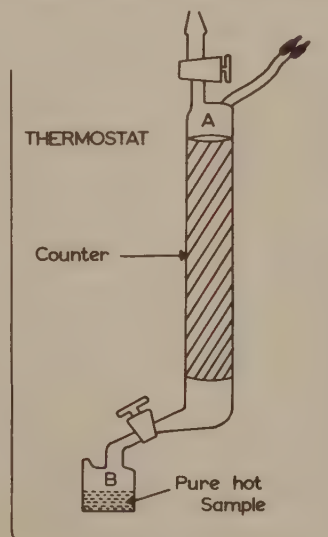


Fig. 1

The basic apparatus is the silver wall gas proportional counter shown in fig. 1. The pure liquid or solid labeled with radioactive tritium is distilled or sublimed into the bulb shown attached to the counter in fig. 1. Then the set up is immersed in a thermostat, the stopcock is opened to the evacuated counter, and the system is allowed to come to equilibrium. The stopcock is then closed and the counting gas is introduced and the counting rate, is measured. The entire

¹) R. S. Rowland, C. N. Truton and R. Wolfgang, J. Am. Chem. Soc. **78** (1956) 2354.

²) R. Wolfgang, J. Eigner and F. S. Rowland, J. Phys. Chem. **60** (1956) 1137.

³) F. S. Rowland and R. Wolfgang, Nucleonics **14** (1956) 58.

⁴) R. Wolfgang, F. S. Rowland and C. N. Truton, Science **121** (1955) 715.

⁵) M. F. A. El-Sayed and R. Wolfgang, J. Am. Chem. Soc. **79** (1957) 3286.

⁶) M. F. A. El-Sayed, R. Wolfgang and P. Estrup, J. Phys. Chem. **62** (1958) 1356.

⁷) K. E. Wilzbach, J. Am. Chem. Soc. **79** (1957) 1113.

procedure can be repeated several times to check reproducibility and to make sure that equilibrium has been established. If the reproducible counting rate is X_T in dis/min at temperature T , S is the specific activity of the substance in $\text{dis min}^{-1} \text{g}^{-1}$ and V is the effective volume of the counter then

$$\frac{X_T}{S} = \quad (1)$$

the amounts in grams, of the vapor of this substance volume V , if isotope effect is neglected.

For these substances, the vapor pressure is so low that we can safely assume an ideal gas behavior and the equation

$$P_T V = nRT \quad (2)$$

can be used. Using eqs. (1) and (2) one gets for the vapor pressure:

$$P_T = \frac{R}{SMV} X_T T \quad (3)$$

where R and M are the gas constant and the molecular weight respectively. S can be determined by transforming an accurately weighed amount of the organic substance into H_2 and CH_4 (by heating with nickel oxide and zinc powder at 670°C for three hours) and then counting the gases. The accuracy of this method depends upon the accuracy in weighing and the accuracy in counting. Both of these techniques can be carried out with very great accuracy.

From the derived equation it is clear that at a constant temperature, increasing S , or V increases X_T for the same substance and thus increases the counting accuracy. Wilzbach's

results show that the specific activity of the radioactive compounds produced by irradiation for comparable periods of time is almost directly proportional to the molecular weight of the compound within a homologous series of organic compounds. Thus, whereas increasing the molecular weight decreases the accuracy of other methods, it will not have much effect on the accuracy of this method. Furthermore, one can usually increase the irradiation time to get more specific activity and/or increase V as substances with higher molecular weights are used or pressures at lower temperatures are to be determined.

There are other advantages of this method, which are due to the nuclear properties of tritium itself. It has a long enough half-life to allow completion of the experiment without experimentally observable loss of activity. On the other hand it has a short half-life compared to other radioactive atoms (e.g. ^{14}C) which makes its specific activity much greater for a given number of radioactive atoms. Its beta energy is so weak that the large amounts of activity necessary for high accuracy does not require great precautions. Finally, there is the fact that hydrogen forms more compounds than any other element in the periodic table.

Related thermodynamic quantities that can be derived from the vapor pressure (e.g. latent heats, activities, molecular weights and especially Henry's constant of solutes) can also be determined. Chemical kinetics might use the principle if a modified apparatus is used.

AUTHOR INDEX

- ALBERIGI, A., C. BERNARDINI and I. F. QUERCIA, Proposal for an analog-to-digital electronic converter suited for nuclear pulse-height analysis . . . 201
- ALVÄGER, T., *see* JOHANSSON
- AMIOU, PIERRE, Device for thermal control of liquid hydrogen bubble chambers . . . 275
- AMR EL-SAYED, MOSTAFA F., A nuclear method for determining very low vapor pressures . . . 359
- ANDERSSON, G., *see* BURGMAN
- ASHBY, NEIL, Relativistic theory of the spherical electrostatic analyzer . . . 90
- BECKMAN, OLOF, Photographic bent crystal gamma spectrometer . . . 27
- BEHMAN, GERALD A., List of particle accelerator installations . . . 181
- BELL, R. E., *see* GREEN
- BELLAMY, E. H., *see* McWHIRTER
- BERKEŠ, BRANKO, Ein besonders einfacher Stromstabilisator höchster Qualität für Elektromagnete 260
- BERNARDINI, C., *see* ALBERIGI
- BIANCHI, L., E. COTTON et C. MILEIKOWSKY, Spectromètre pour particules lourdes . . . 69
- BIRK, M., *see* GOLDRING
- BISI, A. and L. ZAPPA, Statistical spread in pulse size of the scintillation spectrometer . . . 17
- BOOTH, N. E., F. L. HEREFORD and G. W. HUTCHINSON, Internally reflecting Čerenkov counter for high energy protons . . . 229
- BRUECKMANN, R. E., *see* COSTRELL
- BURGERJON, J. J., S. J. DU TOIT and C. A. J. KRITZINGER, The Pretoria cyclotron . . . 323
- BURGMAN, J. O. and G. ANDERSSON, Ion source for radioisotope separation . . . 33
- CAGLIOTI, G., A. PAOLETTI and F. P. RICCI, Choice of collimators for a crystal spectrometer for neutron diffraction . . . 223
- CARPENTER, R. T., *see* SHAFROTH
- CLARKE, R. L., New type of angular-distribution chamber . . . 233
- COLLIDGE, B. and G. B. HUXTABLE, 20 Mc/s scaling circuit . . . 116
- COSTRELL, L. and R. E. BRUECKMANN, Charge-storage pulse-height analyzers for use with pulsed accelerators . . . 350
- COTTON, E., *see* BIANCHI
- DE VILLIERS, J. A. M., *see* MEYER
- DUNJIĆ, B. V., *see* ŠEVARAC
- DU TOIT, S. J., *see* BURGERJON
- ERÖ, J., Radiofrequency modulation in the Thoneman ion source . . . 303
- FARINELLI, U., F. FERRERO and R. MALVANO, Measurement and automatic control of the energy of a 31 MeV betatron . . . 218
- FERGUSON, A. T. G., *see* PHILLIPS
- FERRERO, F., *see* FARINELLI
- FIRK, F. W. K., G. W. REID and J. F. GALLAGHER, High resolution neutron time-of-flight experiments using the Harwell 15 MeV linear electron accelerator . . . 309
- GALLAGHER, J. F., *see* FIRK
- GLOVER, R. N., Aluminium proportional counter for the measurement of low fast neutron flux . . . 316
- GLOVER, R. N., Photofission in fission chambers . . . 320
- GOLDRING, G., M. BIRK, Z. KAMIL and D. MYDANSKY, Method for eliminating the effects of amplitude drifts in measurements of ratios of counting rates (Letter to the Editor) . . . 307
- GREEN, R. E. and R. E. BELL, Notes on a fast time-to-amplitude converter . . . 127
- GRJEBINE, T., *see* PHILLIPS
- GRUHLE, WOLFGANG, Schneller Ringzähler als elektronischer Schalter . . . 204
- GURSKY, JUDITH C., *see* NORTHROP
- HALL, GEORGES, Effets causés par la collection des électrons dans une chambre d'ionisation cylindrique 121
- HANSÉN, J., Read-out system for the Hutchinson-Scarrott analyzer . . . 271
- HEFFERLIN, R. A. and W. E. KREGER, Collimator penetration and scattering effects . . . 149
- HEREFORD, F. L., *see* BOOTH
- HETTINGER, G. and N. STARFELT, Improved NaI scintillation spectrometer for the study of continuous X-ray spectra . . . 25
- HILLAS, A. M. and R. M. TENNENT, High speed counter chronometer . . . 344
- HINTENBERGER, H. and L. A. KÖNIG, Massenspektrographen mit Doppelfokussierung erster Ordnung für alle Massen, die geringe Bildfehler in einem grossen Massenbereich entlang der Photoplatte aufweisen . . . 250
- HINTENBERGER, H., *see* KÖNIG
- HOOGENBOOM, A. M., A new method in gamma-ray spectroscopy: a two crystal scintillation spectrometer with improved resolution . . . 57
- HUSTER, E. and W. RAUSCH, Zur Herstellung sehr dünner elektrisch leitender Präparat-Unterlagen für absolute β -Zählung . . . 213
- HUTCHINSON, G. W., *see* BOOTH
- HUXTABLE, G. B., *see* COLLIDGE
- JOHANSSON, B. and T. ALVÄGER, Proposition for a new method for measuring short half-lives . . . 49

- KAMIL, Z., *see* GOLDRING
- KENDAL, B. R. F., Direct-coupled amplifier for the measurement of small currents 73
- KIRILLOV-UGRYUMOV, V. G., L. P. KOTENKO, E. P. KUZNETSOV and A. V. SAMOILOV, Determination of the masses and momenta of charged particles from multiple scattering measurements in a propane bubble chamber 265
- KÖNIG, L. A. und H. HINTENBERGER, Massenspektrographen mit korrigierten Bildfehlern 133
- KÖNIG, L. A., *see* HINTENBERGER
- KOTENKO, L. P., *see* KIRILLOV-UGRYUMOV
- KREGER, W. E., *see* HEFFERLIN
- KRITZINGER, C. A. J., *see* BURGERJON
- KUZNETSOV, E. P., *see* KIRILLOV-UGRYUMOV
- LINDGREN, INGVAR, Atomic beam resonance apparatus with six-pole magnets for radioactive isotopes 1
- LINDGREN, INGVAR, Investigation of a beta-ray spectrometer with a triangular field 104
- MALVANO, R., *see* FARINELLI
- MCWHIRTER, R. W. P., P. PALIT and E. H. BELLAMY, Distinguishing between He^3 and He^4 particles by " dE/dx " and " E " measurements 80
- MEYER, M. A., P. H. STOKER and J. A. M. DE VILLIERS, Hodoscope system for experiments on the scattering of cosmic ray μ -mesons. Part I – Electronic circuits 278
- MEYER, M. A. and J. A. M. DE VILLIERS, Hodoscope system for experiments on the scattering of cosmic ray μ -mesons. Part II – Performance of the hodoscope 285
- MILEIKOWSKY, C., *see* BIANCHI
- MOREAU, R., *see* PHILLIPS
- MYDANSKY, D., *see* GOLDRING
- NORTHROP, J. A. and JUDITH C. GURSKY, Relative scintillation efficiencies of noble gas mixtures 207
- OHLIN, P., K. SIEGBAHN, T. SUNDRÖM and S. SVENNERSTEDT, Studies of neutron production in linear deuterium pinches 237
- OLKOWSKY, B., *see* PHILLIPS
- OPHEL, T. R., Response curves of alkali halide scintillators with special reference to the $\text{Li}^6(n, \alpha)$ reaction in lithium iodide 45
- PAOLETTI, A., *see* CAGLIOTI
- PALIT, P., *see* MCWHIRTER
- PAUL, E. B., *see* PHILLIPS
- PEROVIĆ, B. Dj., *see* ŠEVARAC
- PHILLIPS, G. C., E. B. PAUL, A. T. G. FERGUSON, A. B. WHITEHEAD, T. GRJEBINE, R. MOREAU and B. OLKOWSKY, Natural modulation of high frequency ion source beams 43
- PROTIĆ, R. M., *see* ŠEVARAC
- QUERCIA, I. F., Electronic apparatus for the measurement of dynamic magnetic fields 292
- QUERCIA, I. F., *see* ALBERIGI
- RAUSCH, W., *see* HUSTER
- REICH, H., Das Entkopplungsglied in der Hf-Transmissionslinie eines Mikrotrons 97
- REID, G. W., *see* FIRK
- RICCI, F. P., *see* CAGLIOTI
- SAAVEDRA, IGOR, On the theory of the diffusion cloud chamber 85
- SAMOILOV, A. V., *see* KIRILLOV-UGRYUMOV
- SCHOPPER, HERWIG, Measurement of circular polarization of γ -rays 158
- ŠEVARAC, I. F., B. Dj. PEROVIĆ, B. V. DUNJIĆ and R. M. PROTIĆ, 60° sector type electromagnetic isotope separator in the Institute of Nuclear Sciences – Belgrade 245
- SHAFROTH, S. M., E. N. STRAIT and R. T. CARPENTER, The response of a NaI(Tl) crystal to monoenergetic neutrons 298
- SIEGBAHN, K., *see* OHLIN
- SKARSVÄG, KRISTIAN, Multiple fast coincidence unit 336
- STARFELT, N., *see* HETTINGER
- STOKER, P. H., *see* MEYER
- STRAIT, E. N., *see* SHAFROTH
- SUBUDHI, K. S., Function of the collecting electrode in a Van de Graaff generator 341
- SUNDRÖM, T., *see* OHLIN
- SVENNERSTEDT, S., *see* OHLIN
- TENNENT, R. M., *see* HILLAS
- TISLJAR-LENTULIS, GEORG, *see* WEINZIERL
- VAN BLADEL, J., General formulas for gap-excited linear ducts 52
- VAN BLADEL, J., Fields in slanted-gap-excited rectangular ducts 109
- WAGNER, S., Umwandlung eines im binären Zahlensystem angezeigten Impulshöhenspektrums in eine registrierte Kurve (Note to the Editor) 119
- WEINZIERL, PETER and GEORG TISLJAR-LENTULIS, Two-crystal-Compton-spectrometer with improved geometrical efficiency (Letter to the Editor) 177
- WHITEHEAD, A. B., *see* PHILLIPS
- ZAPPA, L., *see* BISI

BOOK REVIEWS

- KAHAN, T. and M. GAUZIT, Physique et calcul des réacteurs nucléaires vol. I (ROLF PERSSON) 179
- GAUZIT, M. and T. KAHAN, Contrôle et protection des réacteurs nucléaires vol. II (ROLF PERSSON) 179
- GRAUL, E. H., STRAHLENSYNDROM – Radioaktive Verseuchung (ARNE HEDGRAN) 179

SUBJECT INDEX

Accelerators

Natural modulation of high frequency ion source beams, G. C. PHILLIPS, E. B. PAUL, A. T. G. FERGUSON, A. B. WHITEHEAD, T. GRJEBINE, R. MOREAU and B. OLKOWSKY	43
General formulas for gap-excited linear ducts, J. VAN BLADEL	52
Fields in slanted-gap-excited rectangular ducts, J. VAN BLADEL	109
List of particle accelerator installations, GERALD A. BEHMAN	181
Measurement and automatic control of the energy of a 31 MeV betatron, U. FARINELLI, F. FERRERO and R. MALVANO	218
High resolution neutron time-of-flight experiments using the Harwell 15 MeV linear electron accelerator, F. W. K. FIRK, G. W. REID and J. F. GALLAGHER	309
The Pretoria cyclotron, J. J. BURGERJON, S. J. DU TOIT and C. A. J. KRITZINGER	323
Function of the collecting electrode in a Van de Graaff generator, K. S. SUBUDHI	341

Counters, Chambers and Detectors

Response curves of alkali halide scintillators with special reference to the $\text{Li}^6(n, \alpha)$ reaction in lithium iodide, T. R. OPHEL	45
On the theory of the diffusion cloud chamber, IGOR SAAVEDRA	85
Effets causés par la collection des électrons dans une chambre d'ionisation cylindrique, GEORGES HALL	121
Zur Herstellung sehr dünner elektrisch leitender Präparat-Unterlagen für absolute β -Zählung, E. HUSTER und W. RAUSCH	213
Internally reflecting Čerenkov counter for high energy protons, N. E. BOOTH, F. L. HEREFORD and G. W. HUTCHINSON	229
New type of angular-distribution chamber, R. L. CLARKE	233
Device for thermal control of liquid hydrogen bubble chambers, PIERRE AMIOT	275
The response of a NaI(Tl) crystal to monoergic neutrons, S. N. SHAFROTH, E. N. STRAIT and R. T. CARPENTER	298
Aluminium proportional counter for the measurement of low fast neutron flux, R. N. GLOVER	316
Photofission in fission chambers, R. N. GLOVER	320

Electronic Equipment

Direct-coupled amplifier for the measurement of small currents, B. R. F. KENDALL	73
Das Entkopplungsglied in der Hf-Transmissionslinie eines Mikrotrons, H. REICH	97
20 Mc/s scaling circuit, B. COLLINGE and G. B. HUXTABLE	116
Umwandlung eines im binären Zahlensystem angezeigten Impulshöhenspektrums in eine registrierte Kurve (Note to the Editor), S. WAGNER	119
Notes on a fast time-to-amplitude converter, R. E. GREEN and R. E. BELL	127
Proposal for an analog-to-digital electronic converter suited for nuclear pulse height analysis, A. ALBERIGI, C. BERNARDINI and I. F. QUERCIA	201
Schneller Ringzähler als elektronischer Schalter, WOLFGANG GRUHLE	204
Ein besonders einfacher Stromstabilisator höchster Qualität für Elektromagnete, BRANKO BERKEŠ	260
Electronic apparatus for the measurement of dynamic magnetic fields, I. F. QUERCIA	292
Method for eliminating the effects of amplitude drifts in measurements of ratios of counting rates (Letter to the Editor, G. GOLDRING, M. BIRK, Z. KAMIL and D. MYDANSKY	307
Multiple fast coincidence unit, KRISTIAN SKARSVÅG	336

Fusion

Studies of neutron production in linear deuterium pinches, P. OHLIN, K. SIEGBAHN, T. SUNDSTRÖM and S. SVENNER STEDT	237
---	-----

Instruments for Nuclear Spectroscopy

Atomic beam resonance apparatus with six-pole magnets for radioactive isotopes, INGVAR LINDGREN	1
Relativistic theory of the spherical electrostatic analyzer, NEIL ASHBY	90

Instruments for Nuclear Spectroscopy (*continued*)

Read-out system for the Hutchinson-Scarrott analyzer, J. HANSÉN	271
Hodoscope system for experiments on the scattering of cosmic ray μ -mesons. PART I – Electronic circuits, M. A. MEYER, P. H. STOKER and J. A. M. DE VILLIERS	278
Hodoscope system for experiments on the scattering of cosmic ray μ -mesons. PART II – Performance of the hodoscope, M. A. MEYER and J. A. M. DE VILLIERS	285
Radiofrequency modulation in the Thoneman ion source, J. ERÖ	303
High speed counter chronometer, A. M. HILLAS and R. M. TENNENT	344
Charge-storage pulse-height analyzers for use with pulsed accelerators, L. COSTRELL and R. E. BRUECKMANN	350
A nuclear method for determining very low vapor pressures, MOSTAFA F. AMR EL-SAYED	359

Isotope Separators

Ion source for radioisotope separation, J. O. BURGMAN and G. ANDERSSON	33
60° sector type electromagnetic isotope separator in the Institute of Nuclear Sciences – Belgrade, I. F. ŠEVARAC, B. DJ. PEROVIĆ, B. V. DUNJIĆ and R. M. PROTIĆ	245

News Items

First international symposium on nuclear fuel elements (Columbia, 1959)	308
---	-----

Nuclear Spectroscopy Measurements

Proposition for a new method for measuring short half-lives, B. JOHANSSON and T. ALVÄGER	49
Distinguishing between He^3 and He^4 particles by " dE/dx and " E " measurements, R. W. P. McWHIRTER, P. PALIT and E. H. BELLAMY	80
Measurement of circular polarization of γ -rays, HERWIG SCHOPPER	158
Relative scintillation efficiencies of noble gas mixtures, J. A. NORTHPROP and JUDITH C. GURSKY	207
Determination of the masses and momenta of charged particles from multiple scattering measurements in a propane bubble chamber, V. G. KIRILLOV-UGRYUMOV, L. P. KOTENKO, E. P. KUZNETSOV and A. V. SAMOILOV	265

Spectrometers

Statistical spread in pulse size of the scintillation spectrometer, A. BISI and L. ZAPPA	17
Improved NaI scintillation spectrometer for the study of continuous X-ray spectra, G. HETTINGER and N. STARFELT	25
Photographic bent crystal gamma spectrometer, OLOF BECKMAN	27
A new method in gamma-ray spectroscopy: a two crystal scintillation spectrometer with improved resolution, A. M. HOOGENBOOM	57
Spectromètre pour particules lourdes, L. BIANCHI, E. COTTON et C. MILEIKOWSKY	69
Investigation of a beta-ray spectrometer with a triangular field, INGVAR LINDGREN	104
Massenspektrographen mit korrigierten Bildfehlern, L. A. KÖNIG und H. HINTENBERGER	133
Collimator penetration and scattering effects, R. A. HEFFERLIN and W. E. KREGER	149
Two-crystal-Compton-spectrometer with improved geometrical efficiency (Letter to the Editor), PETER WEINZIERL and GEORG TISLJAR-LENTULIS	177
Choice of collimators for a crystal spectrometer for neutron diffraction, G. CAGLIOTI, A. PAOLETTI and F. P. RICCI	223
Massenspektrographen mit Doppelfokussierung erster Ordnung für alle Massen, die geringe Bildfehler in einem grossen Massenbereich entlang der Photoplatte aufweisen, H. HINTENBERGER und L. A. KÖNIG	250



Spotlight on Industry

This section appears each month and features various happenings of interest in the nuclear industrial world and objective information on products of the nuclear manufacturers. It is offered entirely as a service and all nuclear

manufacturers are cordially invited to submit clearly objective and descriptive material on their endeavors and product developments for consideration for use in this section.

DRAWING MACHINE

*Ad. Auriema, Inc., 85 Broad Street,
New York 4, New York*

Sensitive Research Instrument Corp. announces that "SCAMA", the machine which they have been using for "hand-drawing" their instruments scales for the past 30 years, is now being made available commercially.

thereby provides protection against overexposure in experiments where radiation is emitted. Designed particularly for use with high-voltage particle accelerators such as the Van de Graaff generator, the instrument covers current ranges from one milli-ampere to three milli-microamperes in 12 switch settings.

extremities. Small adjustments can be made to obtain accurate cut-off at either end of the scale.

NUCLEAR PUMPS

*Byron Jackson Pumps, Inc., P. O.
Box 2017, Terminal Annex, Los
Angeles 54, Calif.*

A four-page bulletin describes a complete line of centrifugal pumps for all types of nuclear pumping applications. All three basic types are covered... liquid metal, liner-motor and mechanically-sealed pumps... with general description and capacity ratings of each.

INSTRUMENTS

MODEL A309 CURRENT INDICATOR AND INTEGRATOR

*Elcor, Inc., 1225 West Broad Street,
Falls Church, Virginia*

The primary application of the A309 Current Integrator relates to high-voltage particle accelerators.

The integrator contains an internal calibrating current source that enables the accuracy and performance to be conveniently checked. The instrument's panel switch includes one which allows ready adaptation for measuring current of either polarity.

*AVO Limited, Avocet House, 92-96
Vauxhall Bridge Road, London, S.W.1*

REMOTE INDICATOR DOSE RATEMETER

This equipment has been designed to meet special requirements where it would be dangerous for an operator to expose himself directly to radiation hazards. It consists of two parts, an ionisation chamber, and an indicating instrument which can be located at a distance of approximately 15 ft from the ionisation chamber. The measurement of dose rate is presented on a 5 in. meter scale, the first reading being 0.1 r/h. The scale, which is logarithmic, covers $3\frac{1}{2}$ decades, the maximum reading being 500 r/h.

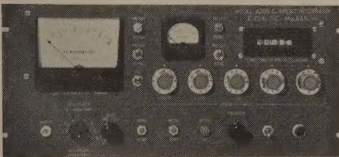
PRECISION PULSE GENERATOR

*Sunvic Controls Limited, Temple Bar
7064*

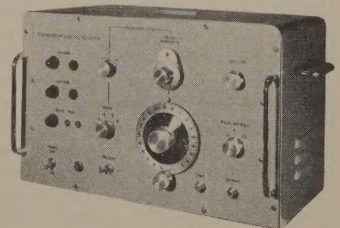
The instrument consists of three main sections: stabilised power supply, voltage divider network and pulse forming network. Pulse amplitude is adjustable over the range 0-40 V by the main control and there is also incremental control which provides continuous variation over a range of 0-1.2 V with a linear accuracy of ± 2 mV. Overall amplitude stability during an 8-hour period is better than $\pm 0.05\%$ (allowing for mains variation

PHOTO TRANSISTOR RELAY METER

A modified form of moving coil meter, which can be made in various sensitivities and read as a normal instrument. At positions corresponding to zero and full scale deflection, photo transistors are mounted and receive light from a small external source, directed towards them by means of a light conducting plastic rod. In addition to its indicating pointer, the moving coil also carries a "Flag" which is arranged to cut off the light falling upon the photo transistors whenever the pointer is at either of its



There is a special register and a set of five switches to enable a given five-decimal digit count to be pre-set into the instrument. When the register reaches the pre-set number, an internal relay automatically closes and thereby provides a means for actuating a warning bell or light or other auxiliary equipment. The pre-setting feature can be used to control the total amount of charge collected and



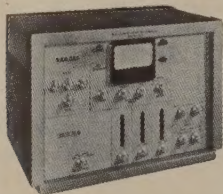
of $\pm 5\%$). A three position switch selects pulse widths of 1, 5 or 25 microseconds. Pulse polarity may be either positive or negative at a repetition rate equal to mains frequency.

Dimensions of the instrument are approximately 11" high $\times$ 19" wide $\times$ 10" deep. Weight: 30 lbs.

A "UNIVERSAL" SCALER

*Nucleonic Corporation of America
196 Degraw Street, Brooklyn 31, N.Y.,
Main*

The "Universal" line features interchangeable slide-out units that "plug-in" quickly, giving any combination of features from simple to complex. Provided for in the "Universal" scaler are outlets for automatic sample changer, and digital or timer print-out equipment. Plug-in amplifier input sensitivities range from a fraction of a millivolt to 9 volts for binary and/or decade scaling units, allowing any scaler function to be performed within the limits of binary 64-4096, and decade 100-1 000 000, simply by adding the units desired.



10-MeV TANDEM ACCELERATORS

*High Voltage Engineering Corporation,
Burlington, Mass.*

The sale of two 10-million electron volt tandem particle accelerators to Switzerland and Australia was announced.

The Van de Graaff machines now under construction are both scheduled for delivery in 1960. One of the machines, consigned to the Swiss Federal Institute of Technology at Zurich, will be installed at the "Kernphysik I" laboratory, about four miles from downtown Zurich. The huge positive ion accelerator will be used for basic nuclear research in reactions produced by charged particles and fast neutrons. The Swiss government-supported program will

be headed by Professor Dr. Pierre E. Marmier of the physics department of the Swiss institute.

The other 10-MeV machine will go to the Australian National University at Canberra and will be used in experiments with hydrogen and deuterium bombardment of light and heavy elements. Professor Ernest W. Titterton, head of the nuclear physics department of the Australian National University, reported the purchase of the tandem accelerator and construction of a new building to house it was made possible through appropriation of special funds by the Australian government.

PAWLING RESEARCH REACTOR

Nuclear Development Corporation of America, 5 New Street, White Plains, N.Y.

The Pawling Research Reactor that has gone into operation (a low power reactor), is a prototype of a Teaching and Research Reactor (TRR) which NDA has developed for university use. PRR will be used for research, nuclear studies and demonstration purposes.

PRR is distinctive among reactors in that it has no self-contained shielding but is, instead, located in a completely shielded room in the reactor critical facility at NDA-Pawling Laboratories. Consequently, when it is not operating, personnel can enter the room and have easy access to all the reactor components. While in operation, the reactor is under observation from the control panel, located in an adjacent room, through closed circuit television.

PRR utilizes heavy water for neutron moderation and plate-type uranium-aluminum alloy fuel elements of well developed technology. The reactor is enclosed in a cylindrical aluminum tank five feet in diameter and four feet high. Surrounding the bottom and sides of the tank is a one-foot layer of graphite blocks. This in turn is enclosed by a layer of homogeneous material (Masonite) several inches thick. The graphite layer reflects escaping neutrons back into the heavy water moderator, while the Masonite is the equivalent of several inches of water in additional reflecting capacity. The entire reactor housing is an octagonal cylinder nine

feet in diameter and seven feet high.

The PRR is licensed by the Atomic Energy Commission to operate at a normal power level of 5 watts, with occasional operation up to 100 watts.

The PRR core consists of 40 plate-type fuel elements of uranium-aluminum alloy construction. In all, the core contains one kilogram (2.2 lbs.) of fully enriched uranium.

PRR contains a number of automatically safety features.

1. "Fail-safe" safety rods of cadmium.

2. Any power surge is accompanied by a sharp rise in heat production. A small rise in the temperature of the heavy water moderator will reduce the reactivity below the critical point.

3. The heavy water supply can be dumped rapidly.

The heavy water system includes the reactor tank, a dump tank with quick acting valve located immediately beneath the reactor tank and a pump to circulate the water. The water is pumped through a filter and a resin purification bed.

Contamination of the heavy water by light water vapor present in the atmosphere is prevented.

CONTINUOUS LEVEL GAGE

*Radiation Counter Laboratories, Inc.,
5121 W. Grove, Skokie, Illinois*

RCL's Continuous Level Gage, Model 40104, measures the level of liquids in totally enclosed containers of any size and dimensions with accuracy to a few hundredths of an inch. Continuous readings are provided in depth or volume.

A small radioactive source contained in a float follows the level of liquid along a path predetermined by guide lines placed inside the tank. Radiation emitted by the source is detected by a scintillation detector located outside the tank. Changes in the level of the liquid cause changes in the strength of radioactivity detected. This change is then calibrated in linear distance or volume.

Among the gage's many applications is its ability to determine the amount of natural gas contained in underground storage cavities. The gage measures the level of water pumped into the cavity to force out the gas. The amount of gas remaining can then be determined.